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AREA-INTENSITY RELATIONSHIPS AND BRIGHTNESS

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AND BRIGHTNESS

BY

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ABSTRACT

AREA-INTENSITY RELATIONSHIPS AND APPARENT BRIGHTNESS

by

Kathleen A. O'Donnell
University of New Hampshire, December, 1982

The change in brightness due to an increase in the size of a test stimulus is termed spatial (areal) summation. The aim of the present research is to quantify spatial summation effects for a large range of stimulus sizes at two suprathreshold luminance levels and two stimulus presentation methods (binocular and haploscopic). Two experiments were performed. In the first experiment, the brightness matching technique was employed and in the second experiment, a magnitude estimation task was utilized. Brightness was found to increase when stimulus area increased. This brightness change was greater when stimulus luminance was high, than when stimulus luminance was low. Method of stimulus presentation had no effect on apparent brightness. These results are compared to other findings reported in the literature.

I. INTRODUCTION

Man is a unique creature in that he can reflect upon and study the nature of his own existence. History has awarded many facets and titles to that existence, such as soul, psyche, mind or behavior. One undeniable dichotomy has remained. There are two parts to the existence of man: the individual, that is, the interpretations, ideas, responses, behaviors, etc. of a person, and the environment, or all the external stimulation that impinges upon an individual's sense organs. The philosophers speculate on how these parts interact with regard to the origin and limits of knowledge; the psychologists attempt to quantify the relationship between them. In other words, a psychologist measures (or controls) environmental stimulation and measures an individual's response to or perception of it. These two measures can then be compared. The importance of such work is twofold. First, the information it renders can be used to improve the human condition. Optimal and noxious amounts and types of environmental stimulation can be identified and regulated in an attempt to make the life of an individual more harmonious with his surroundings. Secondly, it adds to the increasing pool of knowledge related to how the human form is constructed and how the human form functions. This must be of intrinisic interest to man if he is to survive and prosper through future generations. The study of vision and visual processes is especially important since this is the sense upon which man relies the most.

In vision, the physical stimulus that normally initiates a perception is light. There are a number of measurable parameters of light that yield various visual perceptions. The wavelength of a light in large part determine its hue. Also, the intensity or luminance of a light generally determines how bright the light is perceived to be.

The brightness of a spot of light, however, varies with a number of parameters other than luminance. Some of these are duration, position on the retina that is stimulated, pre-exposure adaptation, and luminance of the surrounding area. There is some evidence that size may also be a factor. The change in brightness due to an increase in the size of a test stimulus is termed spatial (areal) summation. The aim of the present research is to quantify spatial summation effects and to identify factors that create changes in those effects.

In the dissertation that follows, there is a review of the research done on spatial summation. Literature reporting spatial summation effects at threshold levels of luminance (i.e. when the stimulus is just detectable) is discussed first, and literature reporting spatial summation effects at suprathreshold luminance levels (i.e. when the stimulus is well into the range of human visibility) is discussed next. This is followed by a brief discussion of the effect of glare sources on the brightness of a stimulus and why glare may be an important factor for determining how to present a stimulus. The reasons for conducting the dissertation experiments are then stated, and the hypotheses are presented. In the first experiment, the brightness matching technique is described and the results are presented. Following this is a description of the second experiment, in which a magnitude estimation task was used, and the results of this experiment are presented. A discussion of the results from both experiments and possible underlying physiology of the spatial summation effect concludes the dissertation.

Background

The relationship between stimulus size and intensity of a light with regard to initiation of a threshold response has long been known (Forster, 1857; Aubert, 1865). Ricco (1877) proposed an equation to describe this relationship when the stimulus is imaged on the fovea of the human eye. The equation stated that the product of the area and intensity of a stimulus is equal to a constant; that is, at threshold, area and intensity are inversely proportional to one another. An equation describing area-intensity relationships with regard to the peripheral retina was proposed by Piper (1903). It states that the square root of the area is inversely proportional to the intensity of the stimulus. Both of these equations have since been shown to hold only for a small range of areas. Lohle (1929) found that Ricco's law holds in the fovea and periphery for visual angles less than 10 min of arc. Although Piper's law still refers only to peripheral excitation, it holds only if the visual angle subtended by the stimulus is between 2 and 7 degrees. Lohle demonstrated that the intensity threshold did not change with a change in area for stimuli with very large areas.

In an attempt to account for area-intensity relationships over a more inclusive range of areas, Wald (1938) proposed the following equation based on differing threshold values for various visual receptors: $(A-n)^k \times I = C$, where A equals area, I equals intensity, n equals the number of excitatory receptors activated and k and C are constants. Increasing the stimulus area causes stimulation of a greater number of low-threshold units. The formula reduces to Ricco's law when k equals 1 and n is small. It reduces to Piper's law when k equals ½ and n is small. Graham, Brown, and Mote (1939) also studied the relationship between stimulus area and intensity for a threshold response in the fovea and periphery of the human eye. These authors proposed an hypothesis to include neural excitation and retinal interaction effects. They believed that the excitation in the nerve fibers associated with an area of retinal illumination varied as a function of their location relative to the illuminated field. The greatest excitation should occur in the center with a graded decrease in excitation toward the perimeter. If the illumination is uniform, then increased excitation at the center (Abney,1897) could only result from an interaction yielding a peak effect at the center. Specifically, they assumed that this peak effect results from an inversely proportional contribution of excitation due to area and some power of the distance of the receptor from the center. They concluded that a simple power function was inadequate to account for area-intensity relationships over a large range of areas; however, it was evident that luminance threshold decreased as stimulus area increased.

It should be noted that the above studies were devoted to area-intensity relationships for threshold responses. Earliest work on area-intensity relationships for stimuli at luminances well above threshold was done by Page (1941). He related the magnitude of pupillary constriction to specific values of area and intensity. He found that pupil constriction increased as retinal illuminance or retinal area increased. The effect of the area-intensity relationship with regard to the human electroretinogram (ERG) was studied by Boynton and Riggs (1951). They measured the height of the b wave in the ERG as a function of the area of small test fields and found that as area increased, the b wave response also increased.

The first psychophysical examination of suprathreshold spatial summation was done by Hanes (1951), who varied the size of a test field and matched it in brightness with a comparison field of constant size at various luminance levels. He found that for low luminance levels brightness increased with increasing stimulus size, but that brightness decreased with increasing stimulus size at high luminance levels. The stimulus sizes in this experiment ranged from 9-144 min of visual angle and the luminance levels ranged from 0.1 to 100.0 mL. Hanes' stimuli were viewed binocularly. That is, the test and match fields together were presented to both eyes.

Diamond (1962) repeated Hanes' experiment, presenting the stimuli haploscopically, which means that one eye of the subject viewed the test field while the other eye viewed the match field. He investigated apparent brightness as a function of stimulus area for both threshold and suprathreshold stimuli. Using the method of limits, Diamond found a systematic decrease in the intensity needed for a stimulus to be detected when the stimulus increased in size. The same systematic relationship was not found for suprathreshold stimulus presentations. These stimuli were spots of light ranging in size from 5.38 to 53.72 min of visual angle. They were presented at luminances ranging from 0.188 to 2.56 log mL. Increased size of stimulis had no effect on apparent brightness for these stimuli. The different results found in these 2 experiments cannot easily be explained. Diamond controlled for pupil size, adaptation and fixation; Hanes did not. It is unlikely that Hanes' lack of controls could have produced the results he obtained. When pupil size is not controlled, the size of the pupil will increase when light levels are decreased. Its size will decrease when the amount of illumination increases. This results in a relative equalizing of light incident on the retina and thus, apparent brightness should change very little or possibly decrease. Uncontrolled adaptation and fixation should result in greater variability in the matches. Thus, these potentially confounding elements would presumably diminish any effects. It is more likely that the difference in the method of stimulus presentation could account for the different results of the two experiments. When the two fields are viewed with both eyes (binocular method), one field may cast stray light onto the other field. Schouten and Ornstein (1939) and Fry and Alpern (1953) demonstrated that apparent brightness of a test field can decrease in such an instance.

Schouten and Ornstein (1939) showed that the apparent brightness of a foveally viewed test stimulus was decreased when a glare source was introduced. This was done using a bipartite circular field. One half of the field (comparison field) was presented to the left eye and the other half of the field (test field) as well as the glare source was presented to the right eye. First, the two half-fields were matched for brightness with the glare source off. Then, the glare source was turned on and a second adjustment made. Schouten and Ornstein write,

> If the objects are matched and shutter U is opened, so that the glare source L becomes visible to the right eye, the test field is suddenly seen to be much darker than the comparison field. After short times of exposure the brightness quickly returns to its original value; after longer times this recovery takes longer, until, after more than five minutes exposure, a final stage as judged by the maximal time of recovery, also about five minutes, seems to be reached.

These authors proposed two mechanisms that might account for the effect: a) stray light from the glare source casts a veiling illuminance over the test image projected on the fovea or b) a physiological effect is created by the glare source that would result in some retinal neural interaction. They favored the latter alternative because they viewed the decrease in brightness of the test field as a drop in sensitivity of the eye exposed to the glare source. They reasoned that had the veiling luminance alternative been true, it would have produced an increase in brightness of the test field. They did not, however, demonstrate that a veiling illuminance would produce an increase in brightness, nor even that it would not produce a decrease in brightness of the test field.

Fry and Alpern (1953) showed that a veiling luminance superimposed on a test field would cause a decrease in brightness of the test field. This situation is analogous to a veiling illuminance projected over an image on the retina. Thus, brightness change due to the onset and offset of a glare source can be explained in terms of the veiling luminance produced by the stray light of the glare source reaching the fovea.

One purpose of the present study was to manipulate the method of stimulus presentation and determine its effect on apparent brightness. In the binocular viewing method, the match field may act as a glare source on the test field and, therefore, affect its brightness. The danger of stray light affecting brightness is removed, however, in the haploscopic stimulus presentation method, because each eye receives light from one stimulus only. This could potentially explain the difference in the results obtained by Hanes and Diamond.

In an attempt to determine whether stray light from the match field was indeed acting as a glare source, the distance between the two fields was also varied. When the separation between the two fields is increased, the images projected onto the retina are also increased in separation. This results in less overlap of stray light and therefore should decrease any differences in the brightness effects resulting from differences in the two conditions of stimulus presentation (binocular and haploscopic).

A second purpose and the general aim of the present study was to clarify and expand the research on suprathreshold spatial summation. In addition to the work of Hanes and Diamond, Torii and Uemura (1965) studied stimuli ranging in size from 36 to 120 min of visual angle at luminances of 1.0, 0.5, 0.0, and -0.5 log mL. They found that brightness decreased gradually with increasing stimulus area at high luminance levels. A slight increase in apparent brightness was found at low luminance levels. These results are similar to Hanes', but stimuli were presented haploscopically in this experiment. Ogawa, Kozaki, Takano and Okayama (1966) investigated a large number of stimulus sizes from 9 to 172 min of visual angle. However, the luminance levels they used were much lower than any previously mentioned (-1.89, -1.54, and -1.35 log mL). Their results showed that apparent brightness of a stimulus increased directly as its size increased. Again, stimuli were presented haploscopically.

Willmer (1954) investigated spatial summation for very small, monochromatic stimuli (0.7 to 13.7 min visual angle). He found that light of 477nm produced results quite different from those produced by 680nm and 577 nm light. Brightness increased with area for stimuli less than 1.4 min for 680nm and 577nm light, but for 477nm light, it increased with area up to 3.5 min. Also, brightness was found to decrease with increasing area for stimuli of 680nm and 577nm light subtending 3.5 to 13.7 min visual angle. This was not found for 477nm light. Higgins and Rinalducci (1975) repeated Willmer's experiment using white light and extending the range of stimulus sizes. They found that brightness increased dramatically for stimuli less than 3.5 min of visual angle and then began to decrease with increasing area. Since brightness increased with increased area with a slope greater than 1, Higgins and Rinalducci termed this "supersummation."

In addition to the brightness matching technique, which was used in all of the previously cited research, a scaling procedure known as magnitude estimation can be used to assess suprathreshold spatial summation. To scale brightness, the subject is asked to assign a numerical value to the amount of brightness he perceives in a test field that varies in size. The value of the test field is to be based on a standard value of brightness assigned by the experimenter to a comparison field of constant size. Thus, if the test field is twice as bright as the comparison field, then the subject should report a number twice as large as the number assigned to the comparison field.

Marks (1971) examined suprathreshold spatial summation using the magnitude estimation procedure. Target sizes were 12, 24, 36 and 60 minutes of visual angle. The targets were presented at six luminance levels between 0.008 and 392.83 mL. He found an increase in brightness with increasing stimulus size. Mansfield (1973), using a greater range of stimulus sizes (3, 43.2, 120 and 240 min visual angle), corroborated these results. The luminance levels he used were 0.629, 6.285 and 62.853 mL for the 3 min target and 0.039, 0.393, 3.928 and 39.283 mL for the remaining target sizes. Parameters other than stimulus size (such as duration of test field exposure) were also manipulated in these studies. This makes it difficult to compare these data directly with the brightness matching data because the same parameters were not manipulated in the brightness matching studies. Thus, it is not clear whether the results obtained from the magnitude estimation studies are due solely to spatial summation effects or an interaction of these effects with the other parameters manipulated.

The present study employed a magnitude estimation task (Experiment 2) as well as a brightness matching task (Experiment 1) to assess brightness. Identical experiment conditions were maintained for both tasks so that the results could be compared directly. This doubled the amount of information obtained in the study and allowed a reliability check between two different psychophysical methods.

It appears that in all the previous research, suprathreshold spatial summation has been found; even Diamond's data show a light effect over his small range of stimulus sizes. Willmer and Higgins and Rinalducci show it for very small stimuli, Ogawa et al show it for very low luminance levels, and Torii and Uemura show it for a large range of luminances, but a small range of stimulus sizes. It also appears for both binocular and haploscopic stimulus presentations. Marks and Mansfield also found it using magnitude estimation. In all these studies, the degree of summation has varied. The studies differ in their range of stimulus sizes, luminance levels investigated, retinal eccentricity of the stimuli, method of stimulus presentation, and standard field size. This makes it very difficult to compare and combine these results with one another. There is no study of this phenomenon that has been systematically done for a large range of stimulus sizes at a high and low luminance level using both the brightness matching and magnitude estimation techniques. The effect of retinal eccentricity and method of stimulus presentation have not been researched at all for this effect. Therefore, it was the purpose of the present study to systematically vary all of these parameters, making it the most inclusive study of suprathreshold spatial summation to date.

The expected findings for the present study are threefold. First, the author expects that brightness of a test field will increase when the size of the field increases. Also, the luminance of a test field needed to match a standard field is expected to decrease as test field size increases. This has been demonstrated in all the previous research findings, with the possible exception of Diamond (1962). It also is expected that this aforementioned luminance and brightness change will be larger when the luminance of the test field is low than when the luminance of the test field is high. Again, this has been demonstrated in the literature. The final hypothesis for this study is that differences in apparent brightness due to the method of stimulus presentation (binocular or haploscopic) will decrease when the test and match fields become further apart. If the fields act as glare sources on each other, then the amount of stray light falling on the fields will decrease when the fields are separated by a greater distance. Thus, any effects the stray light has on brightness will decrease as well. In addition, the magnitude estimation procedure and brightness matching procedure are expected to produce similar results.

II. EXPERIMENT 1

The general purpose of this experiment was to measure the brightness of test fields that were varied in size using the brightness matching technique.

Method

Subjects

One practiced, male observer and one naive, male observer served as subjects. Their visual acuity was assessed as normal, for each eye, by the use of a Snellen eye chart.

Apparatus

Channel A, of a 2-channel optical system, provided a standard field. The second channel, Channel B, provided a match field. Figure 1 shows a schematic diagram of the apparatus. The light source of each path was a 45-w tungsten-halogen lamp (Sylvania no. 6.6A/T2 1/2Q/CL).

In Channel A, lens 1 was used to collimate the light from the light source. Lens 2 was used to focus the light. Lens 3 was used to collimate the light. Lens 4 was used to focus the light and lens 5 was used to collimate it. The light was then reflected off of mirror 1 at a 90 degree angle. Lens 6 focused the light on aperture 1, which consisted of a diaphragm open to .265 inches and was used to eliminate the peripheral edges of the beam. This resulted in a cleaner image on the screen. Lens 7 was used to collimate the light again and lens 8 focused it. Lens 9 collimated the light and lens 10 focused it. Lens 11 produced collimated light and field stop 1 was

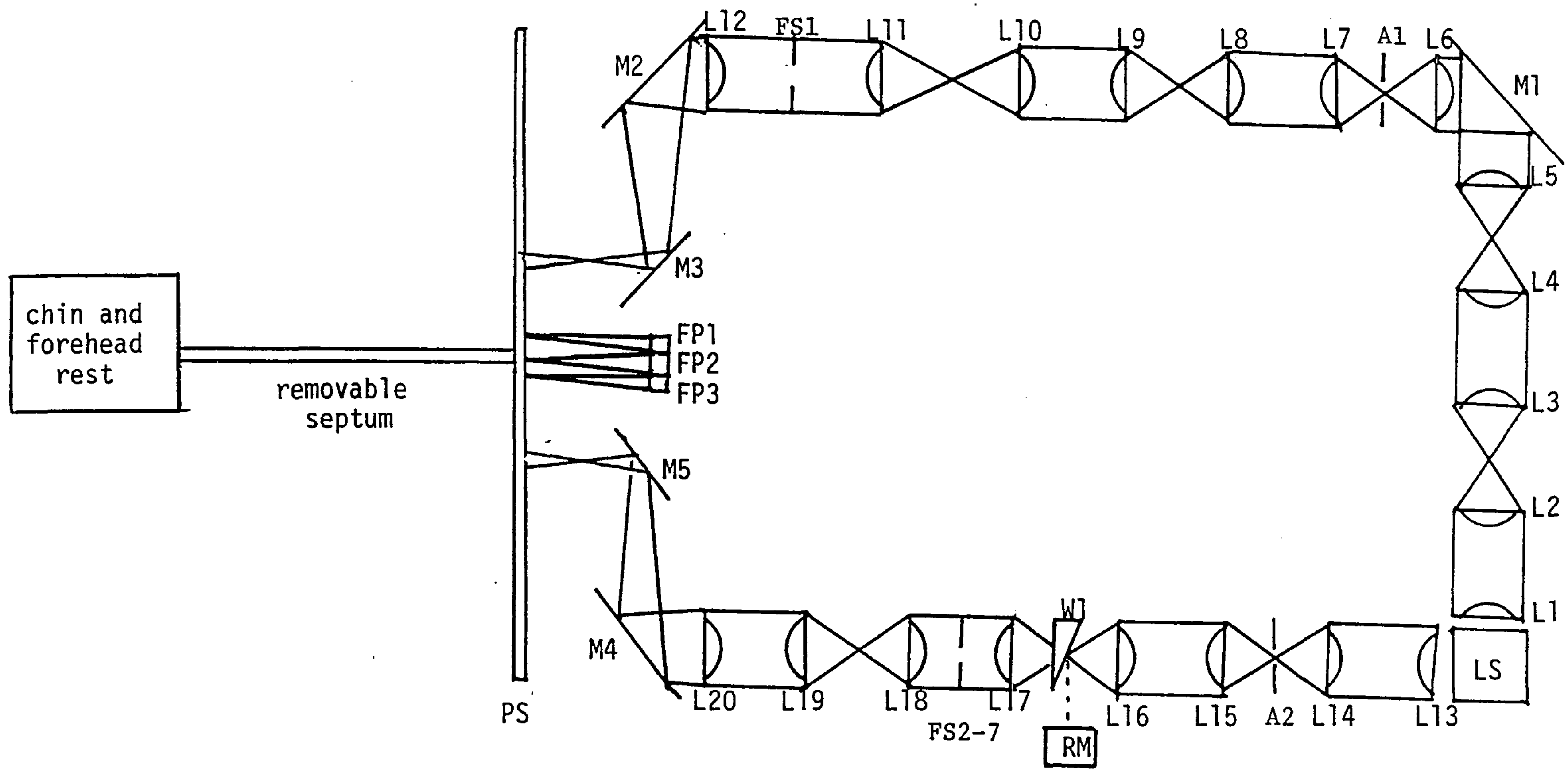

Fig 1.
Schematic diagram of the 2-channel optical system used to provide the standard and match fields. LS - light source, L1-20 - lenses, M1-5 - mirrors, FS1- aperture for standard field, FS2-7 - apertures for match fields, W1 - neutral density wedge, RM - reversible motor to drive wedge, A1-2 - apertures, FP1-3 - lights for fixation points (FP2 - binocular presentation; FP1&3 - haploscopic presentation), PS - paper screen.

placed in this collimated beam. Field stop 1 consisted of a sturdy piece of 2-inch square aluminum with a .344 inch hole in the center. The field stop was supported by a filter holder. It was used to produce the standard field at a constant size of 17.38 min of visual angle. Variations in standard field luminance were produced by placing various combinations of Kodak Wratten neutral density filters in the filter holder just prior to the field stop. Lens 12 was used to focus the standard field on the paper screen. The standard field was first reflected off of mirror 2 at a 90 degree angle, which sent the light parallel to the screen. The light was then reflected off of a second mirror (mirror 3) which placed the image of the standard field on the screen. Increases in the retinal eccentricity at which the standard field was presented were accomplished by moving mirror 3 toward mirror 2. In this way, the image was moved laterally away from the center of fixation. For the binocular condition (see below), fixation was maintained by fixation point 2. Fixation points 1 and 3 were used in the haploscopic condition. The septum was also used in this condition, so the subject was asked to fuse the two fixation points in maintaining fixation.

In Channel B, lens 13 was used to collimate light from the light source. Lens 14 focused the light on a diaphragm used as aperture 2. As in Channel A, the diaphragm was open to .265 inches and was used to eliminate the peripheral edges of the beam. Lens 15 again collimated the light and lens 16 focused it on the neutral density wedge. Luminance of the match field was varied by the neutral density wedge. The neutral density wedge was driven by a reversible motor. The subject was provided with a two-way switch that changed the direction of the motor. Lens 17 collimated the light and a filter holder was placed in this portion of the light. One of 6 field stops (FS 2-7) was placed in the filter holder and determined the size of the match field for a single trial. The field stops were identical to FS 1 with the exception that the central holes in each were .016, .033, .067, .136, .265 and .532 inches. These resulted in match fields that subtended visual angles of 3.16, 6.32, 15.8, 28.44, 56.9 and 110.55 min, respectively. Lens 18 was used to focus the light and lens 19 collimated it again. Lens 20 was used to focus the light onto the paper screen after the light was reflected off of 2 mirrors (mirrors 4 and 5). Mirror 4 reflected the light off at a 90 degree angle, making it parallel to the screen. Mirror 5 also reflected the light at a 90 degree angle, which imaged the match field on the he screen. As with mirror 3, mirror 5 was moved laterally toward mirror 4 to increase retinal eccentricity and the separation between the standard and match fields.

Light from both channels rear-illuminated a paper screen. A paper screen was used because it had negligable directional effects on the transillumination. This was checked in the following way. The luminance of one match field size was measured with a photometer at 45, 90 and 135 degree angles to the field. All luminance measures were within.05 mL of one another.

Directly facing the screen and 68 inches away from it was placed a chin and forehead rest with viewing holes. Artificial pupils were not used. Instead, pupil size was assessed for all the different luminance values of the standard field and all the luminances of the match field settings. This was done by converting the luminance values to cd/m^2 and referring to Table 14 in LeGrand (1968). The table presents pupil size as a function of luminance in cd/m^2. A function to convert cd/m^2 into trolands was constructed from the table and is presented in the Appendix. Thus, a measure of light incident on the retina was achieved.

For Condition 2 (see below), a septum was placed such that it exactly bisected the paper screen and the viewing holes. The septum was made of sturdy cardboard that was painted with flat black paint and covered with black felt. This prevented the septum from acting as a glare source. In this way, only one eye saw what was projected on the screen to one side of the septum and the other eye saw only what was projected on the screen on the other side of the septum.

Luminance was measured using a Litemate/Spotmate Photometer (model 501/502) made by the Photoresearch Corporation. Calibration of background luminance was accomplished by turning on the optical system and blocking both channels of light to the screen. Photometric measurements were taken of various parts of the screen to ensure that the background was homogeneous. Following this, the photometer was placed opposite the standard field and luminance measurements were obtained for Channel A when no filters were present. For Channel B, the same procedure was followed and the neutral density wedge was adjusted for maximum transmission. Luminance was measured in this way for both the standard and match fields at each eccentricity for which they were to be presented. Background luminance was measured at 0.02134 mL or 1.2 trolands. Light baffling was employed wherever necessary to eliminate stray light.

To calibrate the filters, an illuminance measure was obtained with a single filter in Channel A. That filter was replaced by another filter and another illuminance measure was obtained. This pattern continued until the supply of filters was exhausted. The log of the ratio of non-filtered illuminance to filtered illuminances yielded density values for each filter. The neutral density wedge was calibrated in a similar fashion. Wedge positions were labelled from 0 to 239. Light was maximally transmitted through the wedge when it was positioned between 61 and 70. The amount of light transmitted through the wedge decreased as wedge position increased from 70 to 239. Wedge positions of 0 to 60 produced progressively greater decreases in transmitted light than the amount transmitted at 239. Density measures were taken at every tenth wedge position. Density values for the remaining wedge positions were interpolated.

Procedure

The subject was seated facing the screen and looking through the viewing holes. The viewing distance (distance from the subject's eye to the screen) was 68 inches. An example of what the subject saw is shown in Figure 2. The standard field was on the subject's left and the match field was on his right. First, the subject dark-adapted for 10 min then light-adapted for 3 min to the view. The subject then varied the luminance of the match field by adjusting the neutral density wedge, until the match field was equal in brightness to that of the standard field.

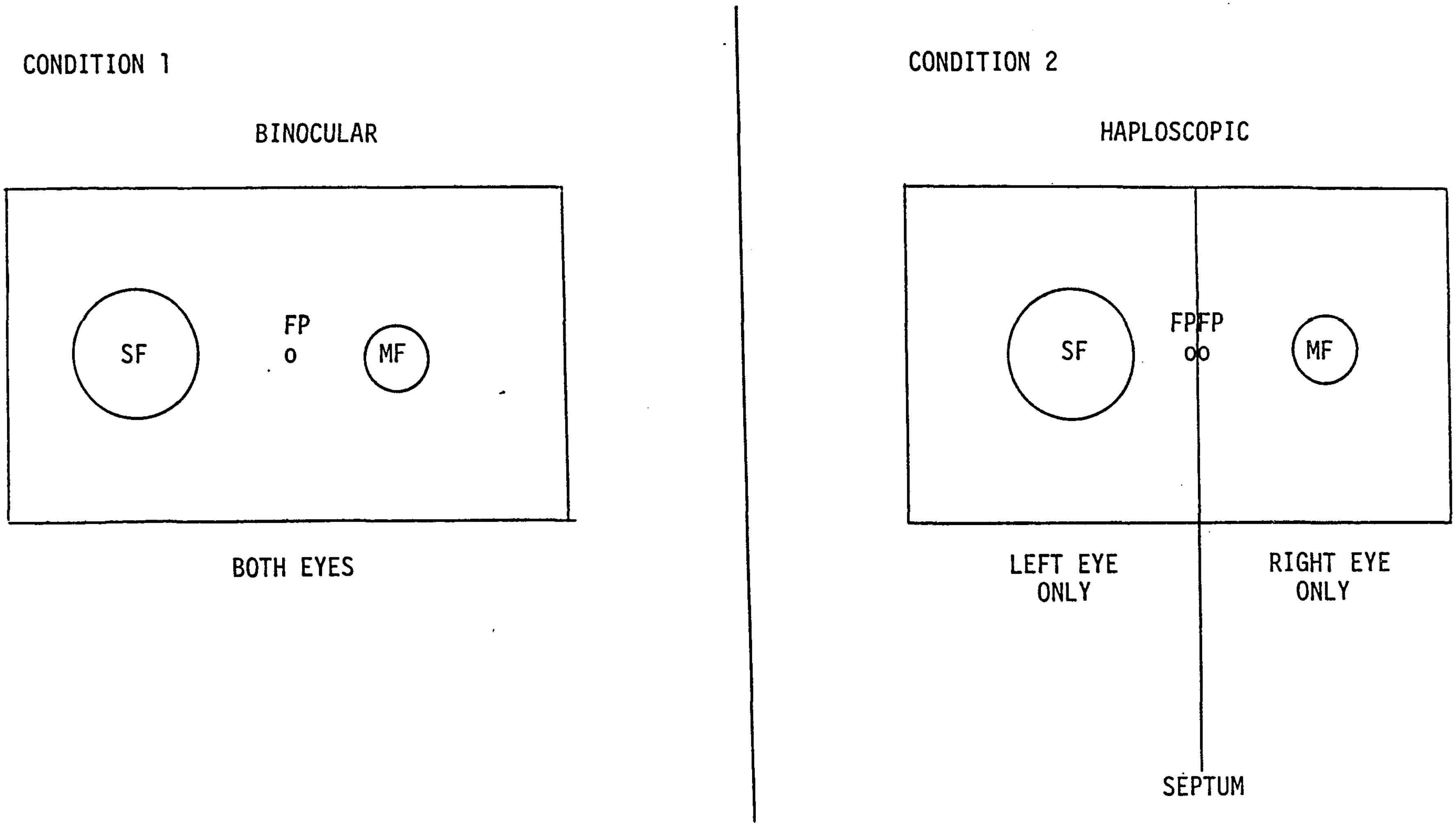

Fig 2. Example of what the subject saw in the two conditions of each experiment. The binocular condition is on the left and the haploscopic condition is on the right. The subject was instructed to fuse the two fixation points in the haploscopic condition. SF - standard field, MF - match field, FP - fixation point.

There were two conditions in each experiment. In Condition 1, the stimuli were presented binocularly. The subject was seated with his head in the chin and forehead rest. There was no septum present, and a single fixation point was employed. The subject was instructed to fixate the small red fixation point. In Condition 2, the stimuli were presented haploscopically. Again, the subject was seated with his head in the chin and forehead rest, but the septum was in place. The septum bisected the center of the screen and the distance between the subject's viewing holes. Two red fixation points were presented. The two points were presented on opposite sides of the septum and were as close to the septum as possible. The subject was instructed to fuse the two fixation points and to keep them fused during a trial. Both conditions were presented under two levels of luminance: -0.4 log mL or 23.9 trolands and -1.3 log mL or 4.6 trolands. Brightness was assessed at both luminance levels and at five different retinal eccentricities. The standard and match fields were separated by 1, 2.5, 5, 7.5 and 10 degrees from center to center. Since the subject was fixating the central point between these two stimuli, the separations resulted in eccentricities of 0.5, 1.25, 2.5, 3.75 and 5 degrees.

In a given session, one luminance level, one eccentricity and one stimulus presentation method (binocular or haploscopic) was presented. The subject was given one match-field size and told to make 5 consecutive matches to the standard. Consecutive matches to a single field size were used so the adaptation of the eye would not change. The experimenter changed the luminance of the match field in a random manner after each brightness match. A second match-field size was presented and 5 more consecutive matches were made. This continued until all match-field sizes had been shown. The match fields subtended visual angles of 3.16, 6.32, 15.8, 28.44, 56.9 and 110.55 minutes. The standard field subtended a visual angle of 17.38 minutes. This constituted one experimental session. The subject repeated the experimental session at a later time for two reasons: 1) to measure the reliability of the matches across time and 2) to acquire 10 matches per match-field size for any given set of parameters. After a subject had finished two experimental sessions for a given set of the above-mentioned parameters, one of the parameters was changed and another experimental session was begun. This continued until all possible combinations of the above-mentioned parameters had been investigated. The order of stimulus size presentation was changed for all experimental sessions.

Results

Equal brightness contours were constructed for each subject at all conditions. Fig 3 shows such contours for GRM and Fig 4 shows contours for JDA.[1] Log matched luminance (in trolands) is on the axis of ordinates and log stimulus area (in minutes squared) is on the axis of abscissae. The broken curve represents the haploscopic presentation and the solid curve represents the binocular presentation. The two luminance conditions are marked as such.

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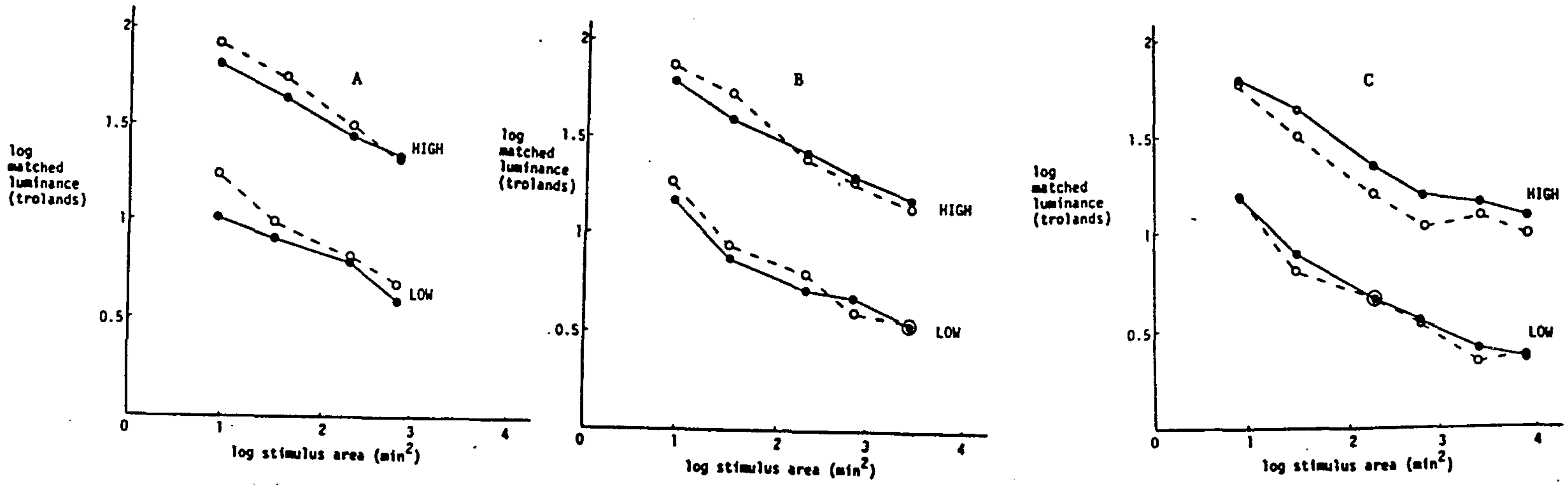
1. For the smallest stimulus separation distances, the largest stimulus sizes could not be used since the fields would, otherwise overlap. Both the 56.9 and 110.55 min fields were eliminated from the 1 deg separation; the 110.55 min field was eliminated from the 2.5 deg separation. All stimulus sizes were presented for the remaining separation distances.



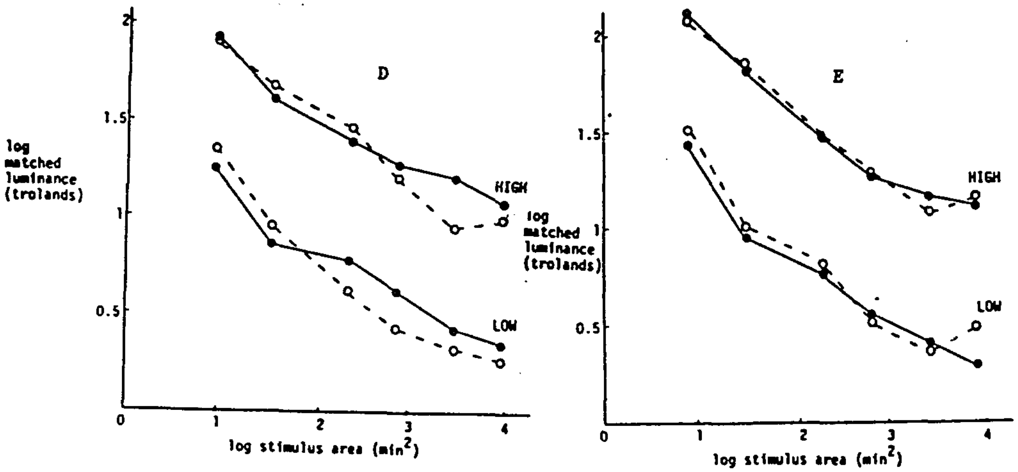


Fig 3. Log matched luminance as a function of log stimulus area for GRM. Filled symbols represent the binocular condition and unfilled symbols represent the haploscopic condition. The luminance levels are marked as high and low. The letters A through E represent the stimulus separation distances. Their values are, respectively, 1.0, 2.5, 5.0, 7.5, and 10 deg of visual angle.

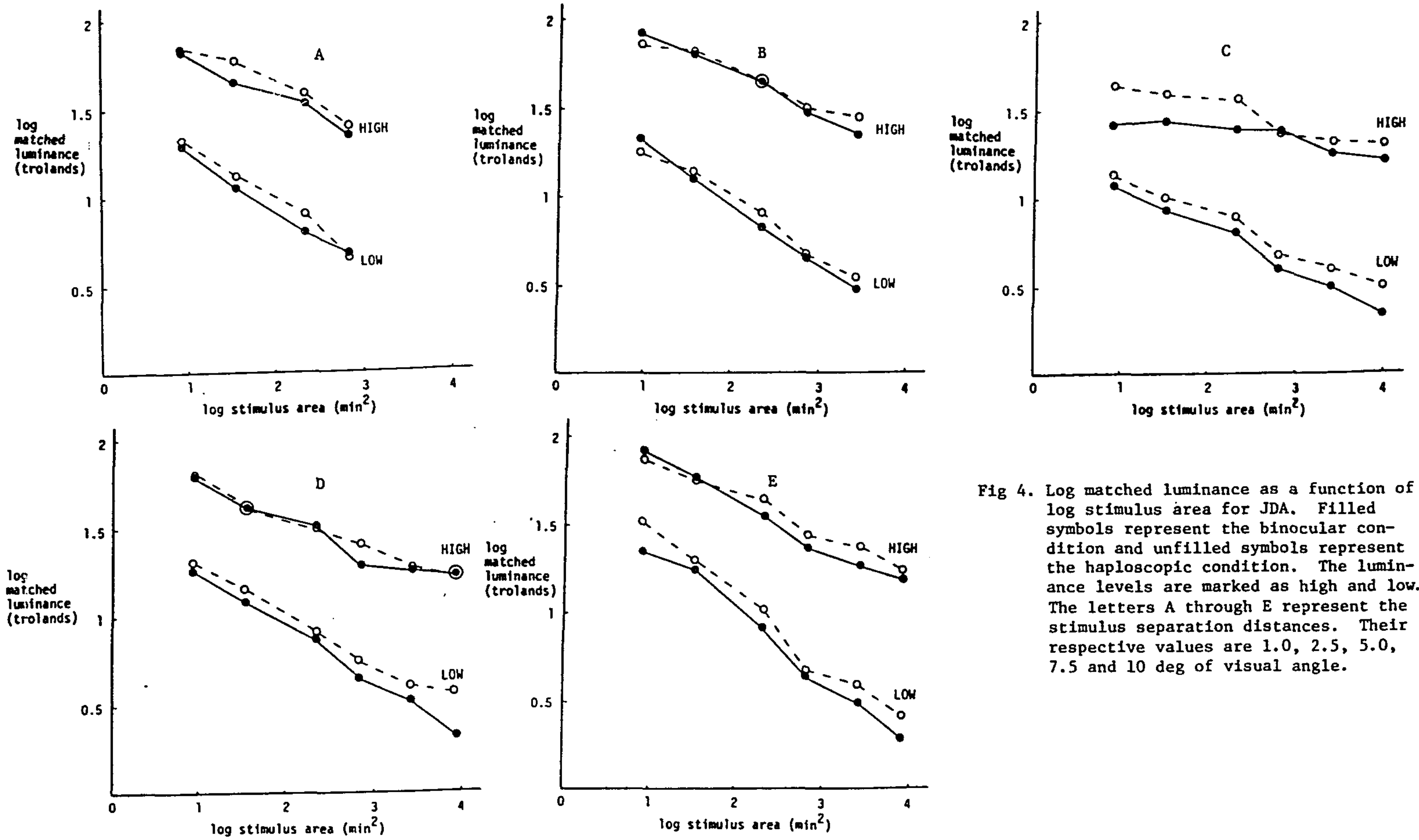


Fig 4. Log matched luminance as a function of log stimulus area for JDA. Filled symbols represent the binocular condition and unfilled symbols represent the haploscopic condition. The luminance levels are marked as high and low. The letters A through E represent the stimulus separation distances. Their respective values are 1.0, 2.5, 5.0, 7.5 and 10 deg of visual angle.

Each point represents the mean of 10 matches made at a given stimulus size. The negative slope exhibited in the results of this experiment suggest an increase in brightness with increasing stimulus size. The data show that when the match field is large, less luminance is required to match the standard field than when the match field is small. Since the standard field, to which all stimuli were matched for brightness, remained constant in both size and luminance, this demonstrates that the large field appears brighter than the small field.

Figs 3A and 4A present data obtained when stimuli were separated by a distance of 1.0 deg of visual angle (0.5 deg retinal eccentricity). It can be seen, for both subjects, that when the match field area was small, greater luminance was required to match the standard field than when the match field area was large. Both subjects showed about the same amount of summation for the high luminance level (slopes: GRM, -0.278 and JDA, -0.237). However, JDA showed greater summation at the lower luminance level than did GRM (slopes: -0.328 and -0.220, respectively). Thus, it can be seen that JDA showed greater summation at the lower luminance than the higher luminance whereas GRM did not. These slope values were the combined averages from the binocular and haploscopic conditions. The local slope values for GRM and JDA can be found in Tables 1 and 2. The lines of best fit were calculated using a standard regression. The R^2 values for both subjects are listed in Table 3.

It can also be noted for these two subjects that there is essentially no difference between the functions produced by the

TABLE I

LOCAL SLOPES FOR GRM
BRIGHTNESS MATCHING TASK

Field Sizes	1HB	1HH	1LB	1LH	2.5HB	2.5HH	2.5LB	2.5LH
3.16- 6.32	-0.299	-0.316	-0.149	-0.382	-0.316	-0.249	-0.465	-0.548
6.32- 15.80	-0.226	-0.314	-0.151	-0.176	-0.239	-0.427	-0.226	-0.188
15.80- 28.44	-0.196	-0.293	-0.431	-0.274	-0.215	-0.157	-0.059	-0.372
28.44- 56.90					-0.083	-0.166	-0.249	-0.116

	5HB	5HH	5LB	5LH	7.5HB	7.5HH	7.5LB	7.5LH
3.16- 6.32	-0.266	-0.449	-0.482	-0.615	-0.532	-0.399	-0.681	-0.664
6.32- 15.80	-0.377	-0.364	-0.276	-0.188	-0.289	-0.276	-0.101	-0.402
15.80- 28.44	-0.313	-0.333	-0.215	-0.274	-0.313	-0.509	-0.293	-0.372
28.44- 56.90	-0.033	0.083	-0.233	-0.299	-0.050	-0.415	-0.332	-0.166
56.90-110.55	-0.121	-0.191	-0.104	0.052	-0.208	0.087	-0.104	-0.104

	10HB	10HH	10LB	10LH
3.16- 6.32	-0.449	-0.316	-0.764	-0.814
6.32- 15.80	-0.490	-0.490	-0.264	-0.251
15.80- 28.44	-0.411	-0.352	-0.391	-0.607
28.44- 56.90	-0.133	-0.337	-0.249	-0.216
56.90-110.55	-0.121	0.156	-0.208	0.208

KEY:

Number in front is stimulus separation distance in degrees visual angle.

First letter is luminance condition - H = high, L = low

Second letter is stimulus presentation condition - B = binocular, H = haploscopic

TABLE 2

LOCAL SLOPES FOR JDA
BRIGHTNESS MATCHING TASK

Field Sizes	1HB	1HH	1LB	1LH	2.5HB	2.5HH	2.5LB	2.5LH
3.16- 6.32	-0.266	-0.083	-0.365	-0.282	-0.183	-0.066	-0.365	-0.149
6.32- 15.80	-0.176	-0.214	-0.352	-0.314	-0.176	-0.201	-0.339	-0.327
15.80- 28.44	-0.352	-0.450	-0.313	-0.509	-0.333	-0.274	-0.372	-0.450
28.44- 56.90					-0.216	-0.100	-0.266	-0.183

	5HB	5HH	5LB	5LH	7.5HB	7.5HH	7.5LB	7.5LH
3.16- 6.32	0.050	-0.100	-0.216	-0.316	-0.299	-0.316	-0.299	-0.233
6.32- 15.80	-0.075	-0.038	-0.163	-0.163	-0.126	-0.151	-0.251	-0.301
15.80- 28.44	0.0	-0.372	-0.411	-0.431	-0.450	-0.157	-0.470	-0.313
28.44- 56.90	-0.166	-0.067	-0.166	-0.033	-0.050	-0.233	-0.199	-0.249
56.90-110.55	-0.087	0.035	-0.260	-0.173	-0.035	-0.069	-0.329	-0.035

	10HB	10HH	10LB	10LH
3.16- 6.32	-0.216	-0.166	-0.233	-0.349
6.32- 15.80	-0.289	-0.163	-0.415	-0.364
15.80- 28.44	-0.372	-0.372	-0.528	-0.646
28.44- 56.90	-0.149	-0.149	-0.233	-0.149
56.90-110.55	-0.139	-0.191	-0.364	-0.312

KEY:

Number in front is stimulus separation distance in degrees visual angle.

First letter is luminance condition - H = high, L = low

Second letter is stimulus presentation condition - B = binocular, H = haploscopic

Table 3

R^2 Values for GRM

Stimulus Separation	Binocular Condition High Lum.	Binocular Condition Low Lum.	Haploscopic Condition High Lum.	Haploscopic Condition Low Lum.
1.0 deg	98.9%	89.7%	100.0%	96.4%
2.5 deg	95.7%	91.9%	95.6%	93.2%
5.0 deg	91.5%	94.8%	85.7%	89.0%
7.5 deg	91.6%	91.8%	94.2%	90.9%
10.0 deg	92.7%	93.7%	90.1%	97.7%

R^2 Values for JDA

Stimulus Separation	Binocular Condition High Lum.	Binocular Condition Low Lum.	Haploscopic Condition High Lum.	Haploscopic Condition Low Lum.
1.0 deg	97.6%	99.9%	87.6%	97.6%
2.5 deg	98.3%	99.7%	96.1%	97.2%
5.0 deg	77.2%	98.5%	84.2%	95.0%
7.5 deg	90.8%	99.2%	97.0%	96.6%
10.0 deg	97.5%	98.8%	98.3%	97.7%

Table 4

t-values for GRM

Stimulus Separation	High Lum.	Low Lum.
1.0 deg	2.088	0.428
2.5 deg	0.075	0.458
5.0 deg	-0.975	-4.475
7.5 deg	0.227	-0.066
10.0 deg	-0.626	-1.593

t-values for JDA

Stimulus Separation	High Lum.	Low Lum.
1.0 deg	-1.108	-17.566
2.5 deg	-1.577	-1.715
5.0 deg	0.138	-0.904
7.5 deg	1.850	0.174
10.0 deg	0.288	-0.009

None of the above t-values are statistically significant.

haploscopic presentation and those produced by the binocular presentation. The corresponding t-values, for both subjects, are listed in Table 4.

Figs 3B and 4B show the matches made when the standard and match fields were separated by a distance of 2.5 degrees of visual angle (1.25 deg retinal eccentricity). These data also show a decrease in luminance needed to match a standard field as the area of the match field increases. GRM shows a slightly greater amount of summation at high luminance than JDA for this condition. Their respective slope values are -0.244 and -0.201. However, JDA shows a slightly larger slope (-0.301) than GRM (-0.255) at the lower luminance level. In this case, both subjects show larger slopes at the low luminance level when compared with the higher luminance level. Local slope values for both subjects are reported in Tables 1 and 2, for this field separation. The R^2 values for both subjects are reported in Table 3.

With regard to the different methods of stimulus presentation, there is clearly no difference between the dashed and solid curves in Figs 3B and 4B for this condition. The t-values for both subjects are reported in Table 4.

The data obtained when the standard and match fields were separated by a distance of 5 degrees of visual angle (retinal eccentricity of 2.5 deg) can be seen in Figs 3C and 4C. Spatial summation is evident in these data as well. The data suggest that in general, the large stimuli would appear brighter than the small stimuli, if they were of equal luminance. Although JDA shows very little summation at the high luminance level with a slope of -0.084, GRM has a slope of -0.243 for the same condition. At the low luminance level, GRM and JDA show a similar increase in summation. The slope values are -0.247 and -0.220, respectively. In this case, JDA shows a clear increase in the amount of spatial summation for the low luminance condition over the high luminance condition. GRM, on the other hand, shows a slight difference in the same comparison. Local slope values are shown in Tables 1 and 2 and R^2 values are shown in Table 3.

As in the other conditions, no difference is evident between the data from the haploscopic condition and data from the binocular condition. The appropriate t-values are shown in Table 4.

Data obtained when the standard and match fields were separated by 7.5 degrees visual angle (3.75 deg retinal eccentricity) are plotted in Figs 3D and 4D. It can be seen for both subjects that the small stimuli need more luminance to match a standard field than the large stimuli. As in the previous separation condition, GRM shows greater summation than JDA for the high luminance level. The respective slopes are -0.295 and -0.181. There is essentially no difference in the amount of summation exhibited by the two subjects at the lower luminance level. GRM shows a slope of -0.310 and JDA shows a slope of -0.277. JDA shows an amount of summation at the low luminance that is greater than the amount he exhibits at the higher luminance level. GRM displays a small difference in brightness changes across the luminance conditions as well. Local slope values, for the 7.5 degree stimulus separation condition, can be found in Tables 1 and 2 and R^2 values can be found in Table 3.

Differences between the binocular and haploscopic stimulus presentation methods were insignificant, as shown in Table 4 by the t-values.

Equal brightness contours obtained for a standard and match field separation of 10 degrees visual angle (5 deg retinal eccentricity) are shown in Figs 3E and 4E. Spatial summation is reflected by the negative slope of all these curves. GRM shows a larger amount of summation at the high luminance level than does JDA. The slope for GRM is -0.332 whereas JDA's slope is -0.229 for this luminance level. At the lower luminance level, both subjects exhibit a comparable amount of summation. GRM's slope value is -0.344 and JDA's is -0.348. As noted before, both subjects show a difference in the amount of summation exhibited at the high vs. low luminance levels. A larger amount of summation is displayed at the low luminance level than at the higher luminance level. Local slope values are in Table 1 and 2 and R^2 values are in Table 3.

Finally, it can be noted in Figs 3E and 4E that there is essentially no difference between the functions produced by haploscopic presentation and those produced by binocular presentation. These t-values can be found in Table 4.

In summary, spatial summation was exhibited for both subjects under all conditions. This is shown in Fig 5. Slope is plotted as a function of stimulus separation distance. As can be seen, the slope values range from -0.08 to -0.37, suggesting that some change in brightness has occurred. No change in brightness would be represented by a slope value of 0.0, and all slope values in the present study are significantly greater than 0.0. JDA clearly shows less summation than GRM at the higher luminance level. This is seen more clearly in Fig 6 where the data have been averaged across conditions of stimulus presentation. JDA's slope values are smaller overall than GRM's for the high luminance level. On the other hand, both subjects display roughly the same amount of spatial summation for stimulus separations of 5 to 10 degrees when the luminance is lower. This is shown by the dashed lines. GRM shows substantially less summation than JDA at the smallest separation distances. Also seen in Figs 5 and 6 is the fact that both subjects show a difference in the amount of summation across luminance condition. GRM shows less of a difference, although, his data are in general qualitative agreement with JDA's. Were it not for a single point (low-luminance, 1 deg separation), GRM would show the same U-shaped function that JDA shows quite clearly.

Lastly, no statistically significant differences were found between results from the binocular presentation and results from the haploscopic presentation. Fig 7 shows this comparison.

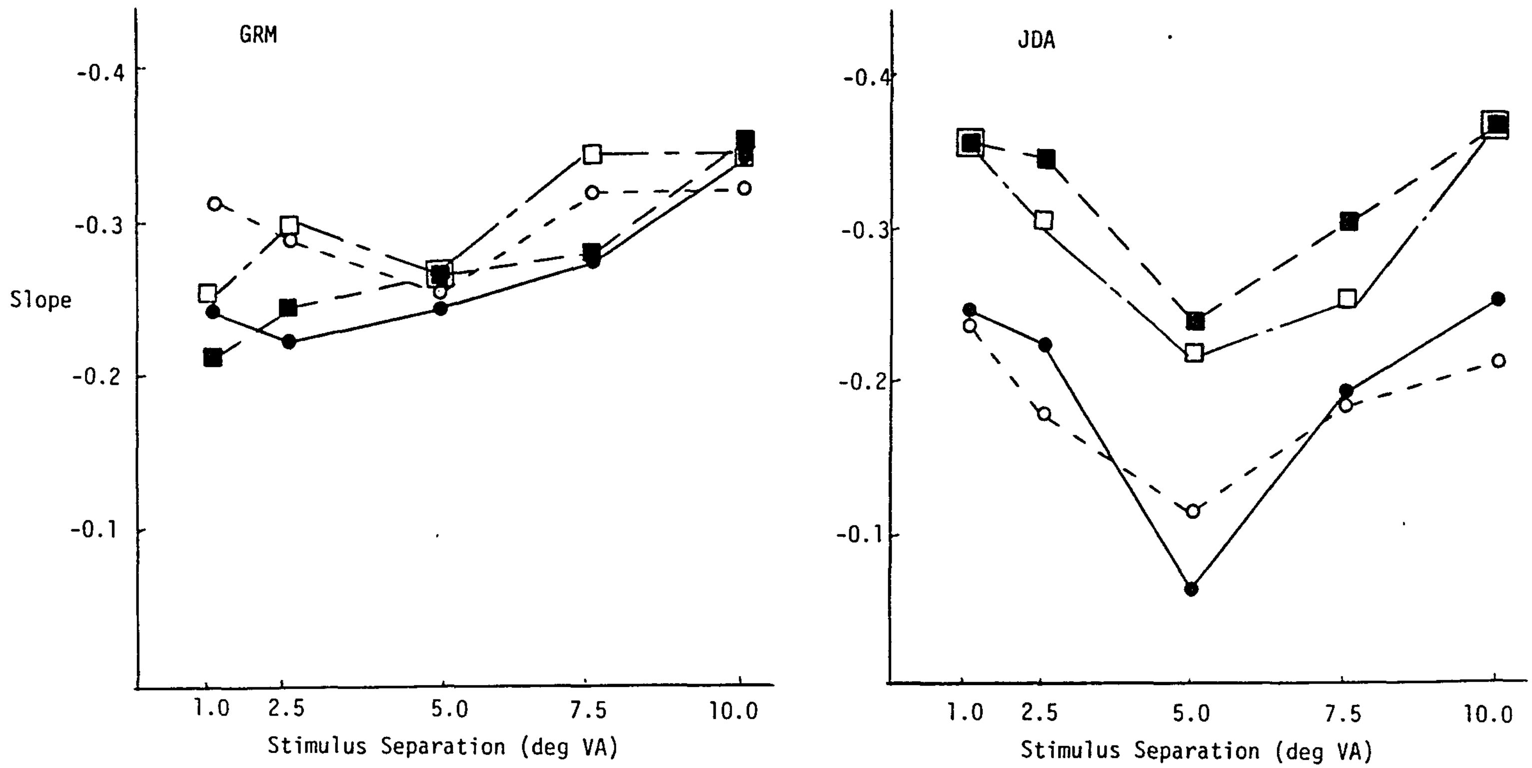


Fig 5. Slope of the equal brightness contours, for both subjects, as a function of stimulus separation distance. Filled symbols represent the binocular condition and unfilled symbols represent the haploscopic condition. Circles represent the high luminance level and squares represent the low luminance level.

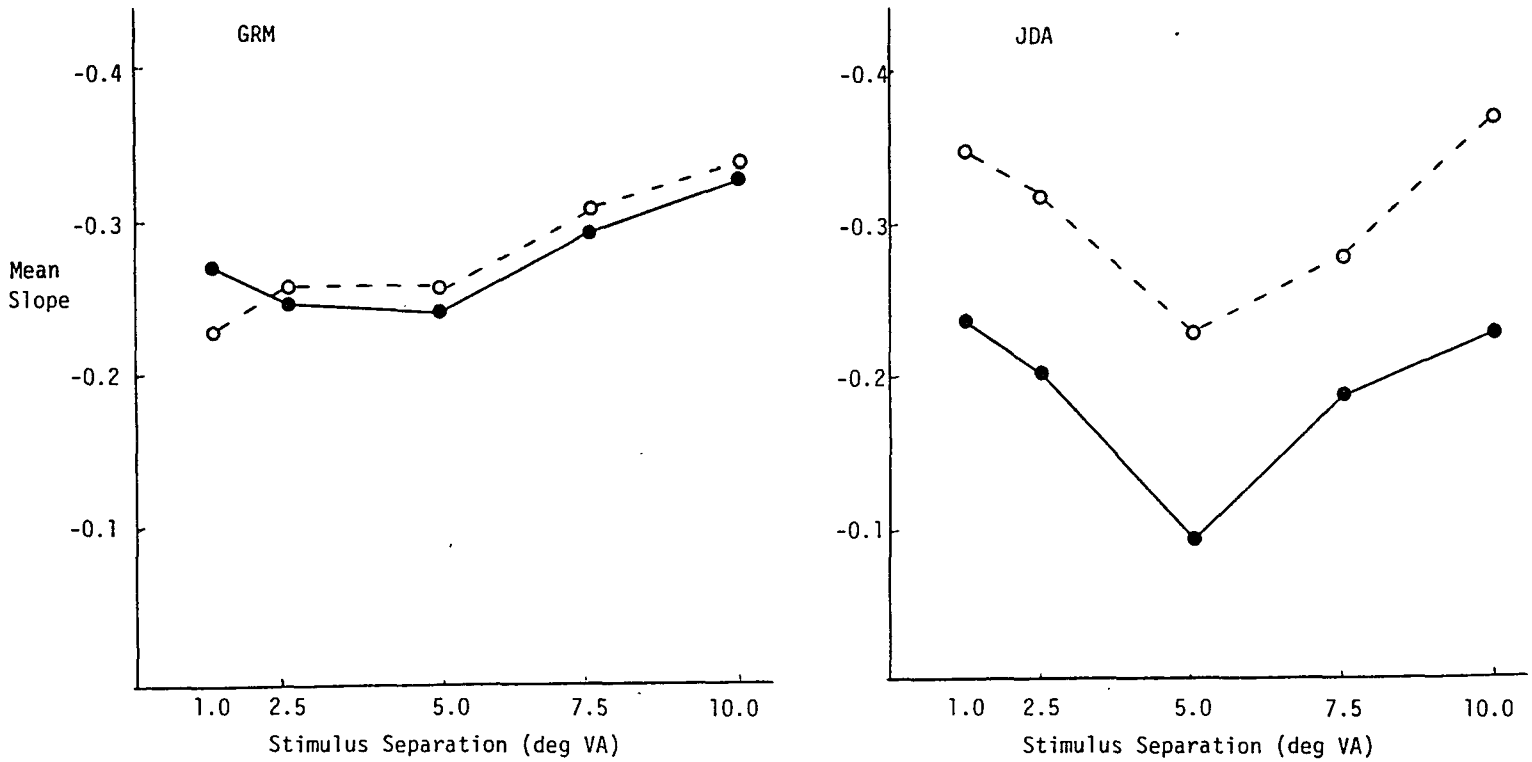


Fig 6. Mean slope of the equal brightness contours, for both subjects, as a function of stimulus separation distance after averaging across conditions of stimulus presentation. Filled symbols represent the high luminance level and unfilled symbols represent the low luminance level.

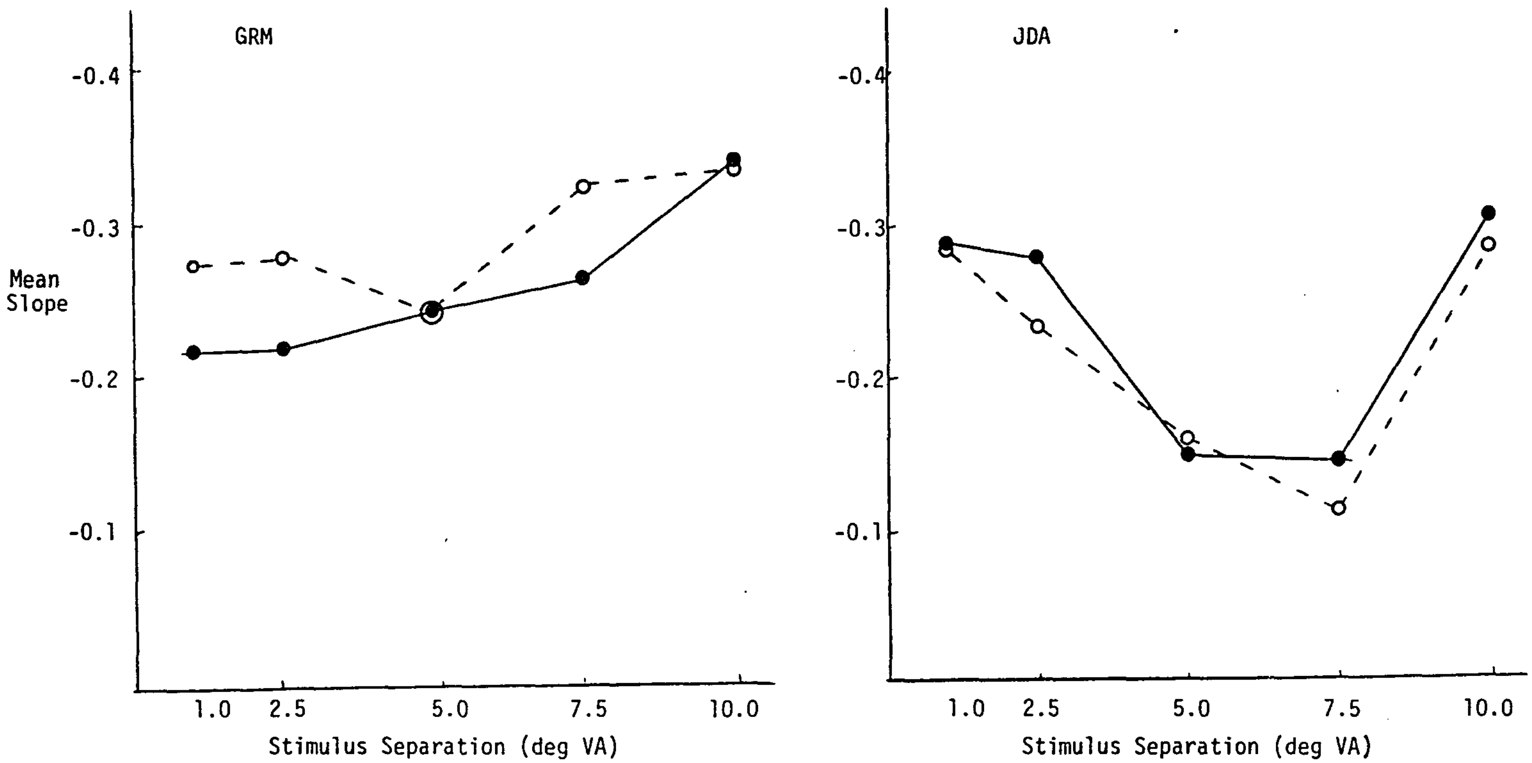


Fig 7. Mean slope of the equal brightness contours, for both subjects, as a function of stimulus separation distance after averaging across luminance levels. Filled symbols represent the binocular condition and unfilled symbols represent the haploscopic condition.

III. EXPERIMENT 2

The purpose of this experiment was to assess changes in the apparent brightness of test fields that varied in size using a scaling technique, magnitude estimation. It was assumed that the findings of Experiment 1 would be supported by the results of this experiment, even though the methods used to assess brightness in the two experiments were different.

Method

Subjects

Two hundred male and female undergraduates participated in partial fulfillment of an Introductory Psychology course requirement.

Apparatus

The apparatus was the same as that used in Experiment 1. Channel B was equated in luminance to Channel A.

Procedure

The subject was first dark-adapted for 10 minutes. He was then seated facing the screen with his head in the chin and forehead rest. The subject was instructed to assess the brightness of the match field by assigning a numerical value to it based on the value assigned to the standard field. The brightness of the standard field always had a value of 10. So, for example, if the match field was twice as bright as the standard field, the subject was instructed to assign the match field a value of 20. The size of the standard field was the same as in Experiment 1. The match field sizes were also the same as in Experiment 1. The two conditions of Experiment 1 were used in Experiment 2 as well. In Condition 1, the stimuli were presented binocularly. In Condition 2, the stimuli were presented haploscopically. Both conditions were presented under the same two levels of luminance as in Experiment 1. The stimulus sizes were presented randomly to each subject, and each subject gave only one brightness estimate per stimulus size. Thus, a single subject was run in only one condition, a single luminance level and a single eccentricity, but he gave a brightness estimate for all stimulus sizes. Estimates were obtained for all stimulus sizes under both presentation conditions, both luminance levels and all five retinal eccentricities mentioned in Experiment 1.

Results

Fig 8 depicts data obtained from all subjects under all conditions. Each point represents the median estimate of 10 subjects.[2] A single curve represents data from the same 10 subjects. Log magnitude estimate is plotted as a function of log stimulus area. Results from the binocular presentation are represented by the filled symbols, and results from the haploscopic presentation are represented by the unfilled symbols. The high-luminance data are plotted as circles, and the low-luminance data are plotted as squares.

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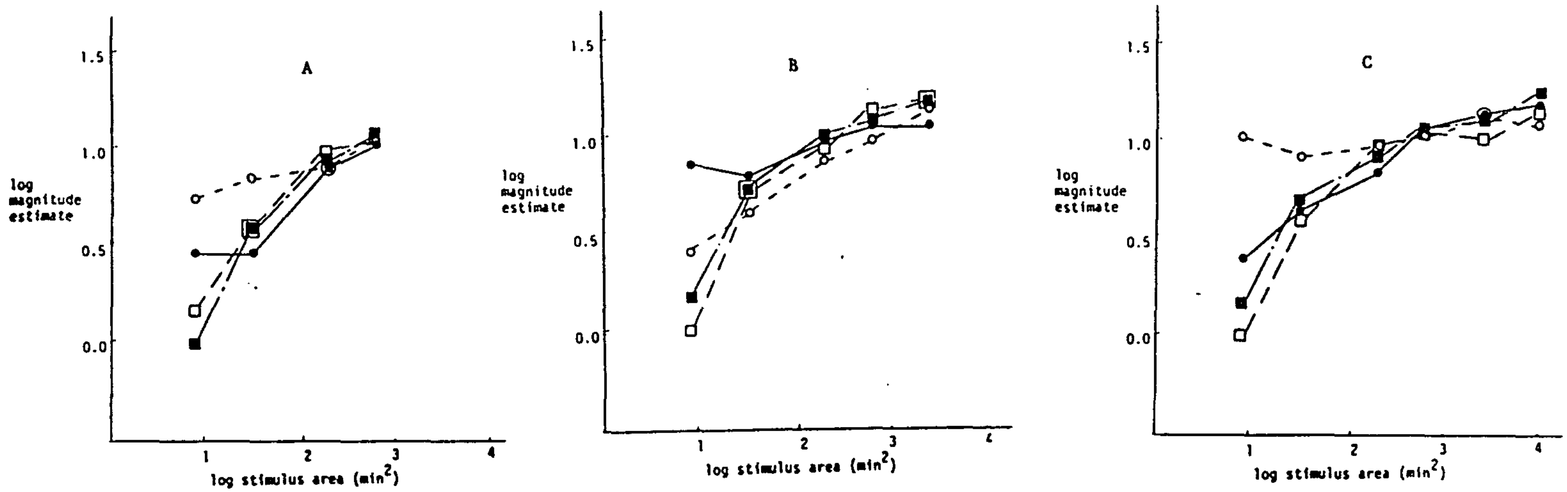
2. The high luminance binocular presentation curve is based on the estimates of 8 subjects. The data of two subjects were discarded from the results because their estimates were vastly different from the estimates given by the remaining eight subjects. In particular, their estimates were uncharacteristically variable, showing standard deviations that exceeded their median estimate values.



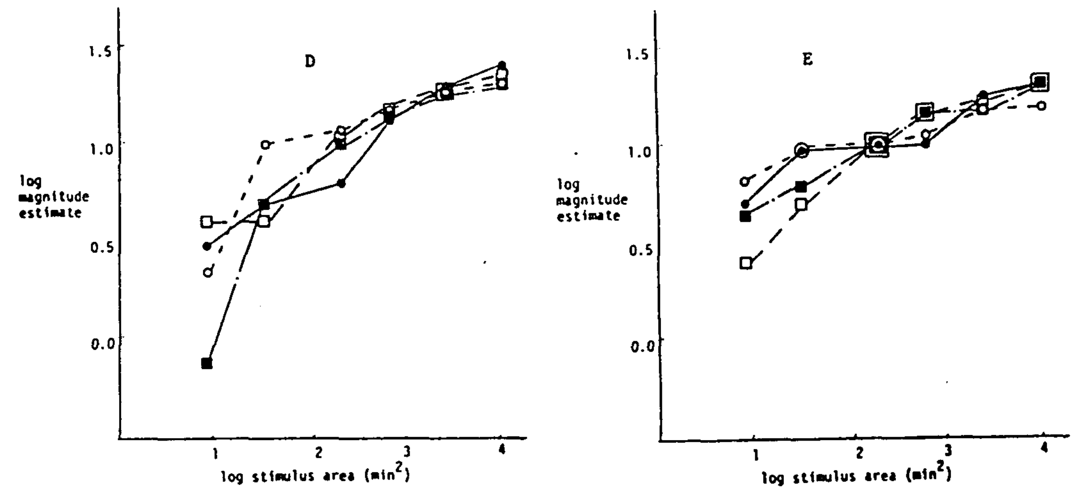


Fig 8. Log magnitude estimate as a function of log stimulus area for all stimulus separation distances. Filled symbols represent the binocular condition and unfilled symbols represent the haploscopic condition. Circles represent the high luminance level and squares represent the low luminance level.

Fig 8A shows the results for the two conditions of stimulus presentation and the two conditions of luminance for a separation distance of 1 degree of visual angle (0.5 deg retinal eccentricity). As in the brightness matching data, apparent brightness increased as the area of the stimulus increased. The amount of this brightness change was greater at the lower luminance level (slope=0.509) than it was at the higher luminance level (slope=0.232). Local slope values are listed in Table 5. A standard regression was used to fit lines to the data. The R^2 values are listed in Table 6.

It can be noted in Fig 8A also that the method of stimulus presentation (binocular vs. haploscopic) appears to have no effect at the lower luminance level. A small difference between the binocular and haploscopic curves is evident for the two smallest stimuli when the luminance level is high. However, neither difference is statistically significant. The t-values for this separation distance are listed in Table 6.

Fig 8B shows log magnitude estimate as a function of log stimulus area when the standard and match fields were separated by 2.5 degrees visual angle from center to center (1.25 deg retinal eccentricity). Spatial summation is evident in these data as well. Brightness of the stimulus appears to increase as the size of the stimulus increases. As at 0.5 deg retinal eccentricity, the brightness change was greater when the luminance level was low (slope=0.395). The high luminance level showed a slope of 0.193. This difference appears to be due to the smallest test fields.

Table 5 also shows local slope values for this stimulus separation distance, and Table 6 shows R^2 values.

It can be seen in Fig 8B that the binocular stimulus presentation yielded a curve virtually identical to the haploscopic stimulus presentation under low luminance conditions. As in Fig 8A, the high luminance level shows a difference between the two presentation methods but, again, it is not statistically significant. The t-values are reported in Table 6.

The data in Fig 8C were obtained when the standard and match field were separated by 5 degrees visual angle (2.5 deg retinal eccentricity). Apparent brightness increased as stimulus area increased. The change in brightness was greater for the low luminance level when compared to the high luminance level. This is demonstrated by slope values of 0.319 and 0.159, respectively. Local slope values for this field separation distance can be found in Table 5, and R^2 values can be found in Table 6.

With regard to binocular vs. haploscopic presentation, there is no difference, whether field luminance is low or high. The t-values can be found in Table 6.

Fig 8D presents log magnitude estimate as a function of log stimulus area for the condition in which the standard and match fields were separated by a distance of 7.5 degrees visual angle (3.75 deg retinal eccentricity). Brightness increased with increased stimulus size. As at the other field separation distances, more summation occurred under the low-luminance (slope=0.347) than under the high-luminance condition (slope=0.291). Local slope values are listed in Table 5 and R^2 values are listed in Table 6.

TABLE 5

LOCAL SLOPES FOR
MAGNITUDE ESTIMATION TASK

Field Sizes	1HB	1HH	1LB	1LH	2.5HB	2.5HH	2.5LB	2.5LH
3.16- 6.32	0.0	0.174	1.000	0.708	-0.078	0.339	0.937	1.229
6.32- 15.80	0.535	0.073	0.411	0.472	0.207	0.343	0.327	0.187
15.80- 28.44	0.231	0.270	0.311	0.162	0.123	0.202	0.119	0.472
28.44- 56.90					0.0	0.253	0.166	0.027

	5HB	5HH	5LB	5LH	7.5HB	7.5HH	7.5LB	7.5LH
3.16- 6.32	0.424	-0.153	0.869	1.000	0.576	1.125	1.369	0.0
6.32- 15.80	0.241	0.089	0.320	0.500	0.643	0.127	0.378	0.551
15.80- 28.44	0.458	0.080	0.245	0.080	0.712	0.192	0.286	0.266
28.44- 56.90	0.136	0.199	0.058	-0.033	0.367	0.149	0.201	0.149
56.90-110.55	0.075	-0.111	0.224	0.161	0.354	0.059	0.059	0.147

	10HB	10HH	10LB	10LH
3.16- 6.32	0.463	0.274	0.145	0.500
6.32- 15.80	0.028	0.028	0.327	0.378
15.80- 28.44	0.0	0.119	0.343	0.346
28.44- 56.90	0.404	0.193	0.0	0.066
56.90-110.55	0.101	0.0	0.215	0.146

KEY:

Number in front is stimulus separation distance in degrees visual angle.

First letter is luminance condition - H = high, L = low

Second letter is stimulus presentation condition - B = binocular, H = haploscopic

Table 6

R^2 Values for Magnitude Estimation Task

Stimulus Separation	Binocular Condition High Lum.	Binocular Condition Low Lum.	Haploscopic Condition High Lum.	Haploscopic Condition Low Lum.
1.0 deg	86.3%	90.1%	92.1%	93.1%
2.5 deg	75.6%	80.9%	98.8%	76.9%
5.0 deg	94.1%	83.4%	43.6%	70.4%
7.5 deg	86.2%	81.5%	69.6%	91.4%
10.0 deg	85.3%	94.2%	90.4%	91.1%

t-values for Magnitude Estimation Task

Stimulus Separation	High Lum.	Low Lum.
1.0 deg	-0.361	-0.425
2.5 deg	0.418	-3.072
5.0 deg	-2.638	-2.756
7.5 deg	-2.422	-0.901
10.0 deg	-0.671	0.506

None of the above t-values are statistically significant.

There is essentially no difference between results obtained from a binocular field presentation and those obtained from a haploscopic field presentation when the luminance level is low. The same appears true for the high luminance level. This is represented by the overlap of the filled and unfilled symbols in Fig 8D. These t-values are reported in Table 6.

Data obtained when the standard and match fields were separated by a distance of 10 degrees visual angle are presented in Fig 8E. As in almost all of the previous conditions, apparent brightness increased when stimulus area increased. This change in brightness was slightly larger when the luminance level was low (slope=0.255). When the luminance level was high, the slope value was 0.144. The local slope values can be found in Table 5, and R^2 values can be found in Table 6.

No differences were evident due to the method of stimulus presentation. This can be seen in Fig 8E and in the t-values reported in Table 6. The filled and unfilled squares generally overlap, as do the filled and unfilled circles.

In summary, brightness increased when field area increased for virtually all conditions. As can be seen in Fig 9A, the amount of brightness change was greater at the lower luminance level. This is represented by the higher slope values for low luminance (unfilled circles) vs. high luminance (filled circles). Local slope values showed that, in general, the most summation occurred between the two smallest field sizes when the luminance level was low. Local slope values showed no real pattern when luminance level was high.

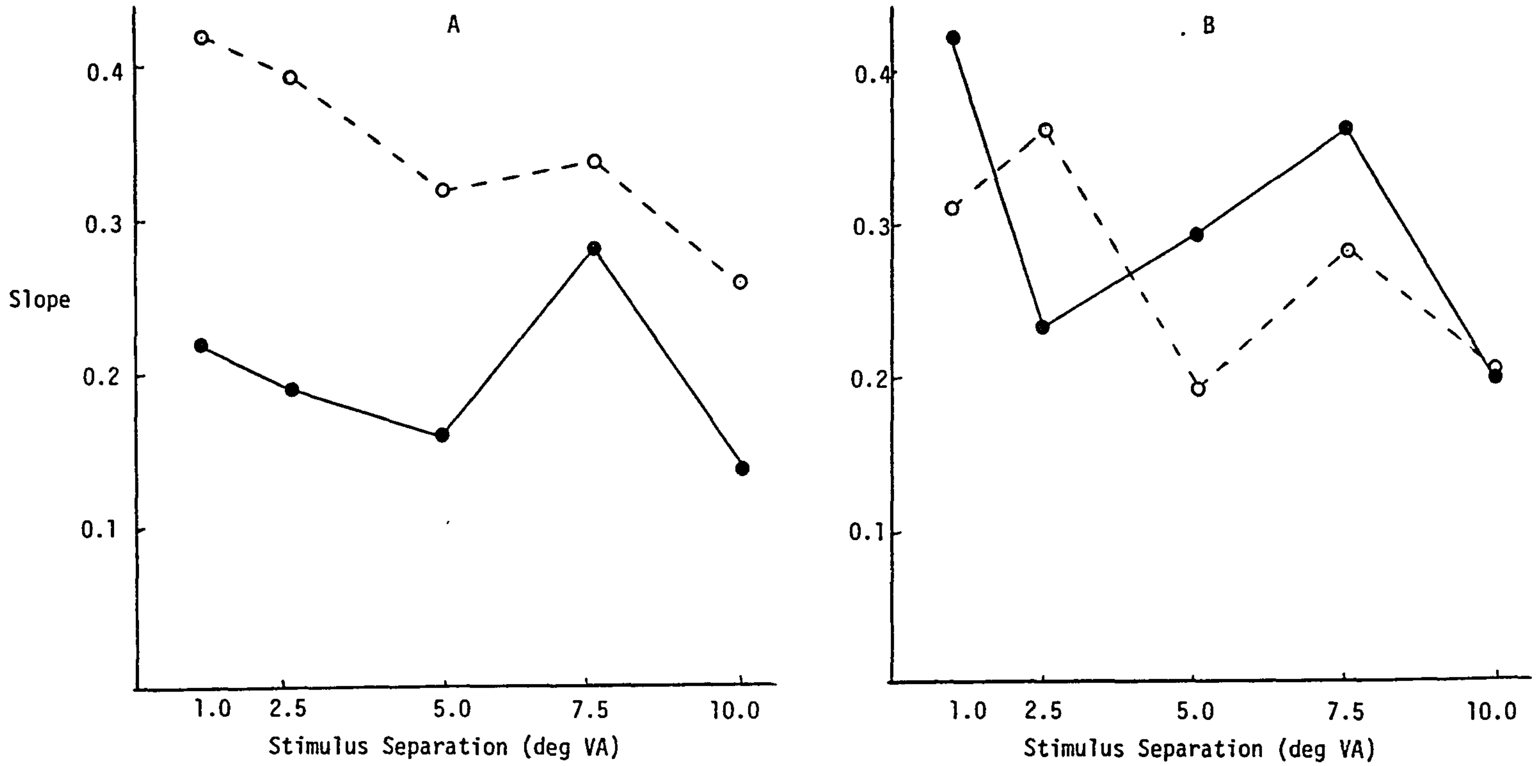


Fig 9. Mean slope of the summation curves as a function of stimulus separation distance after A) averaging across conditions of stimulus presentation and B) averaging across luminance levels. Filled symbols represent the high luminance level in plot A and the binocular condition in plot B. Unfilled symbols represent the low luminance level in plot A and the haploscopic condition in plot B.

Fig 9B shows a comparison of binocular stimulus presentation (filled circles) and haploscopic stimulus presentation (unfilled circles). There appears to be no systematic difference between these two methods of stimulus presentation.

IV. DISCUSSION

In general, for every retinal eccentricity examined (0.5 to 5 deg of visual angle), the apparent brightness of a field increased with increases in its size. These findings are in basic agreement with those reported in the literature. Fig 10 shows a plot comparing results found in the various brightness matching, spatial summation experiments. Hanes (1951) found an increase in brightness with increased stimulus size for his lowest luminances. These luminance levels (0 and -1 log mL) were comparable to the ones in the present study. More summation was found in the present study, however, than was found by Hanes. This can be attributed to the two smallest stimulus sizes employed in the present experiments. These fields were smaller than any fields used by Hanes (9 min was Hanes' smallest field) and provided a sizable contribution to the total amount of spatial summation. This is evident in the local slope values (Tables 1 and 2). The present study also displayed more summation than that found by Torii and Uemura (1965) at comparable luminance levels. Again, this is probably due to the small field sizes used in the present study. The smallest stimulus size employed by Torii and Uemura was 36 min of visual angle. Four of the stimuli in the present study were smaller than 36 min and accounted for most of the spatial summation effects. Ogawa, Kozaki, Takano and Okayama (1966) found also that the brightness of a stimulus increased directly as its size increased. Again, the two smallest stimulus sizes can account for the larger amount of summation found in the present study than that found by Ogawa et al. Higgins and Rinalducci

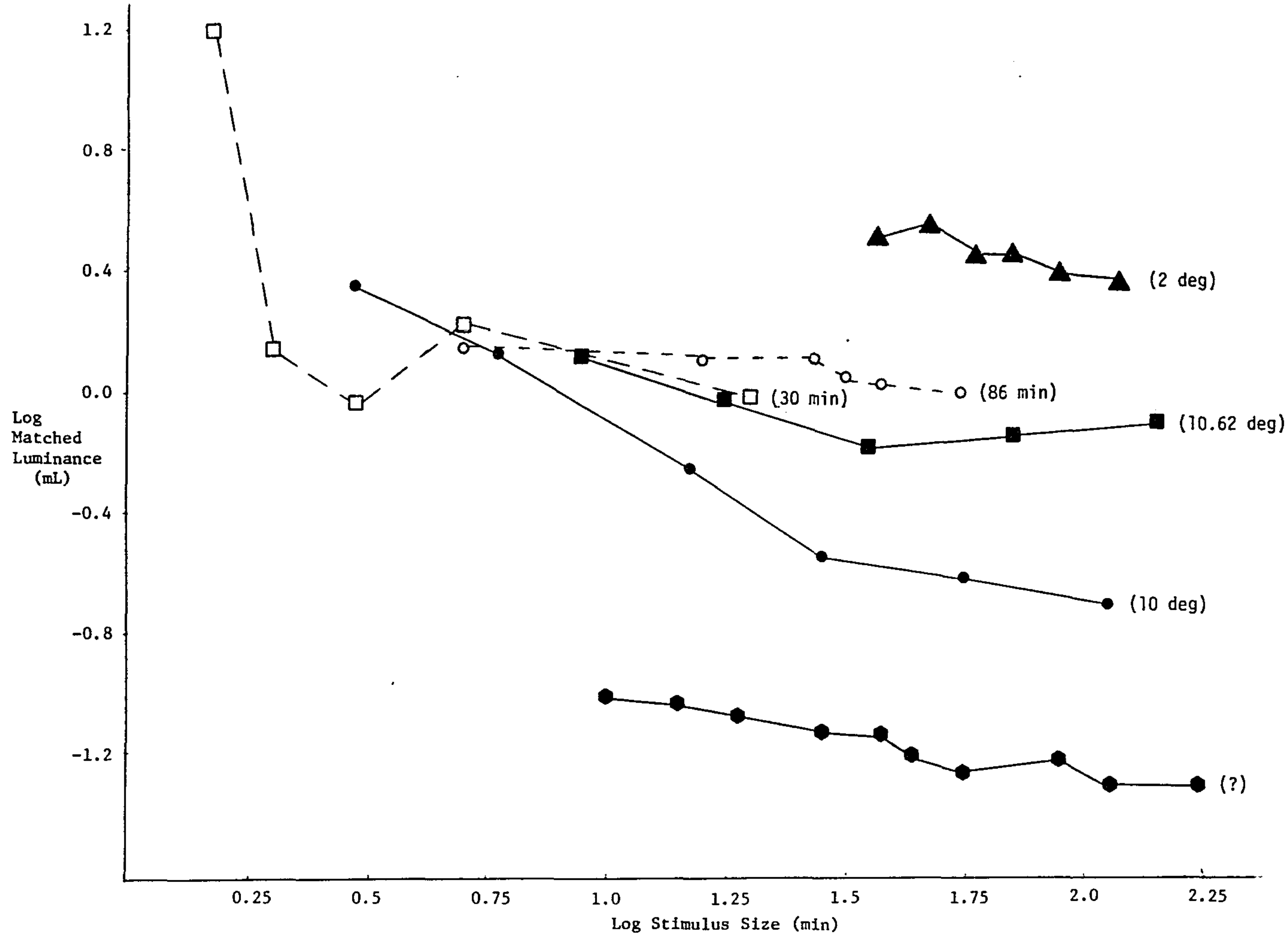


Fig 10. Results from suprathreshold spatial summation experiments that used the brightness matching technique. The unfilled squares are from Higgins and Rinalducci (1975) and the unfilled circles are from Diamond (1962). The filled triangles are from Torii and Uemura (1965), the filled squares are from Hanes (1951), and the filled hexagons are from Ogawa et al (1966). The filled circles are the average of the two subjects in the present study when stimuli were separated by 10 deg visual angle. The number to the right of each curve is the distance (in visual angle) between the stimuli.

(1975), on the other hand, used stimuli much smaller than those in the present study (0.5 to 3.5 min of visual angle) as well as comparable sizes (3.5 to 10.0 min). In this case, Higgins and Rinalducci found the greatest amount of summation for the 0.5 to 3.5 min stimuli. A comparable amount of summation was found for both studies when the common stimulus sizes were compared. It remains a mystery why Diamond (1962) reported little to no spatial summation in his results. His findings are inconsistent with all of the preceding experiments. The two lowest luminances he used were comparable to those used in the present study. Also, the range of stimulus sizes he employed was subsumed by those used in the present study.

The magnitude estimation data as well concurred with former findings in the area. This can be seen in Fig 11. Increased brightness with increased stimulus size was found by Marks (1971). The range of field sizes used by Marks was smaller than that of the present study. When the sizes common to both experiments are compared (6 to 60 min of visual angle) for similar luminance level and retinal location, approximately the same amount of spatial summation is found. The same is true with regard to Mansfield's findings (Mansfield, 1973). Brightness was found to increase when stimulus size increased over a range of 3 to 240 min of visual angle. The greatest amount of spatial summation was found for the smallest stimulus sizes as was true in the present study.

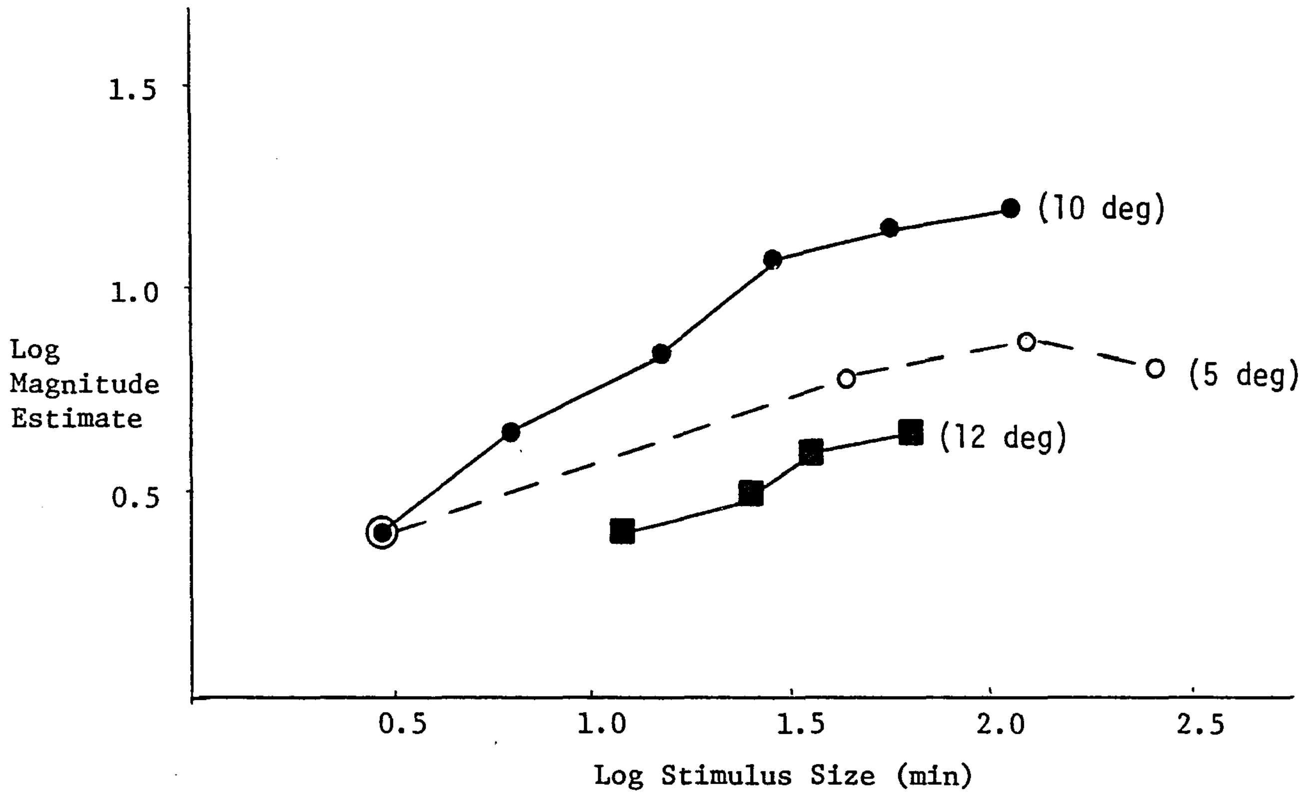


Fig 11. Results from suprathreshold spatial summation experiments that used the magnitude estimation technique. The unfilled circles are from Mansfield (1973) and the filled squares are from Marks (1971). The filled circles are data from the present study when stimuli were separated by 10 deg of visual angle. The number to the right of each curve is the distance between stimuli in deg of visual angle.

The greater increase in brightness change found at the low-luminance level when compared to the high-luminance level also concurred with previous results for brightness matching (Hanes, 1951; Torii and Uemura, 1965; and Ogawa et al, 1966) and for magnitude estimation (Marks, 1971). Any quantitative differences among these findings are probably due to the differences in background luminances among the studies or differences in standard field sizes.

It was surprising that no significant difference was found between the binocular and haploscopic stimulus presentation conditions. An interaction between field separation distance and method of stimulus presentation was expected. The haploscopic and binocular presentations were expected to yield disparate, but parallel, functions when the field separation distance was small. The disparity was then expected to diminish as the two fields were moved further apart, until both presentation methods yielded virtually identical functions. Results of the present study suggest that the standard and match fields did not act as glare sources on each other. This would occur if either one of two situations was present. The fields were too far apart to cast stray light on each other or the luminance of the fields was too low for stray light to affect apparent brightness. Fry and Alpern (1953) used separation distances encompassing those in the present study, but luminance levels greater than in the present study. They found that the glare source significantly affected the brightness of a test field when separated by 1,1.5 and 2.5 deg of visual angle. Since these separations were used in the present study, but brightness was unaffected by glare, it appears that the luminance levels used in the present study were too low to act as an effective glare source. This suggests that studies heretofore using procedures for controlling glare between test fields need not have done so when the luminance levels employed were as low or lower than those in the present study (eg Ogawa et al, 1966).

It is yet to be determined what the critical level of luminance is that will produce significant glare between fields. An experiment comparing binocular stimulus presentation to haploscopic stimulus presentation for a large range of luminance levels is suggested.

Retinal Eccentricity

The effect of retinal locus on suprathreshold spatial summation is relatively unclear. The brightness matching data (Fig 6) suggest a U-shaped function. The amount of brightness change decreases as retinal eccentricity increases from 0.5 to 2.5 deg. As retinal eccentricity increased from 2.5 to 5 deg, however, the amount of spatial summation increases. This is demonstrated effectively in JDA's data and is mildly supported by GRM's data. Unfortunately, the magnitude estimation data (Fig 9) are too variable to yield reliable information either supporting or refuting the brightness matching findings.

There are two possible explanations for the U-shaped function. First, the low slope value for JDA at 2.5 deg retinal eccentricity was the first eccentricity condition to be completed. Since JDA was a naive observer, it is possible that he was still becoming familiarized with the task. If that were the case, it is quite possible that he subsequently changed the criterion he used to determine a match. This possibility would suggest an increase in standard error values for JDA at 2.5 deg retinal eccentricity, however, and this did not occur.

It is also possible that spatial summation effects are minimal around 2.5 deg retinal eccentricity. Osterberg (1935) measured the relative density of receptors across the retina and found they were minimal at approximately 2.5 deg retinal eccentricity. Therefore, a stimulus that increases in size at 2.5 deg retinal eccentricity will stimulate fewer additional receptors than one that increases in size at a retinal eccentricity of higher receptor density. Consequently, apparent brightness should increase less in the former case than in the latter. Individual differences in receptor density as a function of retinal location would account for the difference in degree of non-monotonicity between the two subjects.

Further research on spatial summation effects as a function of retinal eccentricity using a larger range of retinal locations is suggested. A careful investigation of retinal locations immediately surrounding 2.5 deg retinal eccentricity would also prove useful in clarifying these effects.

Experimental Comparison

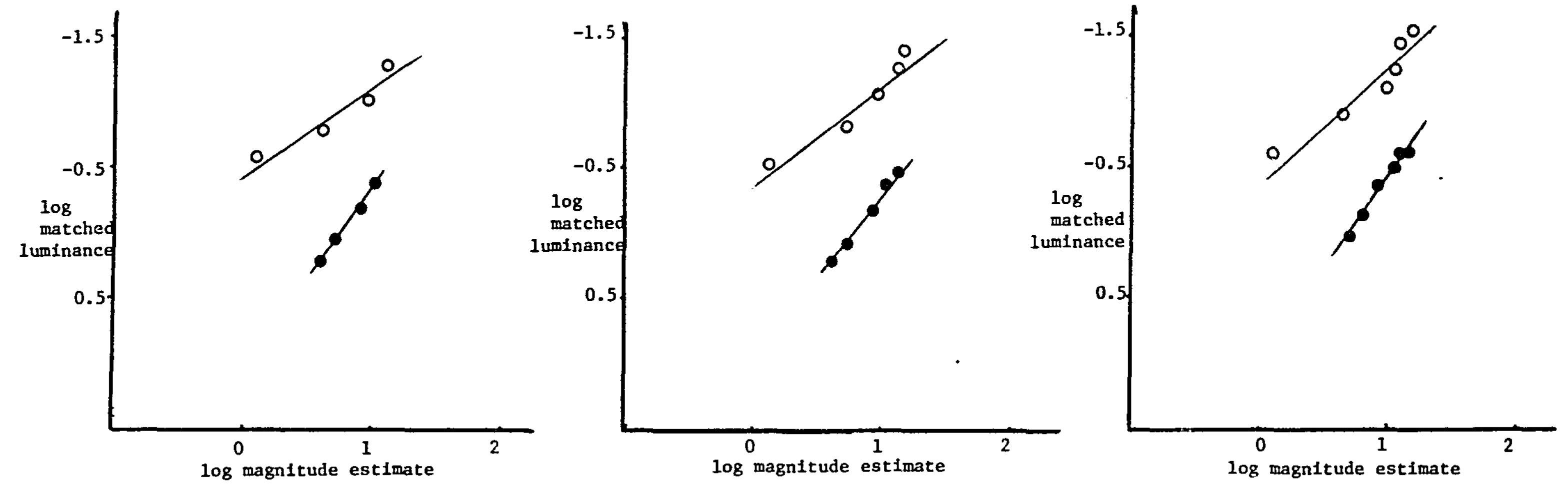
The brightness matching data and the magnitude estimation data are in general agreement with one another. An increase in brightness occurs when target area is increased for brightness matches as well as brightness estimates. More spatial summation is exhibited in the low-luminance condition than the high-luminance condition for both brightness matching and magnitude estimation experiments as well. Finally, both brightness matching data and magnitude estimation data show no differences between the binocular and haploscopic stimulus presentation data.

In addition, the brightness matching and magnitude estimation procedures were compared as tools for assessing changes in suprathreshold spatial summation. This was accomplished by combining the curves generated by the two experiments in the present study. If the two techniques are equivalent brightness assessment measures, a linear function with a slope of 1.0 would be produced when the curves are combined.

Fig 12 shows log matched luminance as a function of log magnitude estimate for all stimulus separation condtions. Both log matched luminance and log magnitude estimation values were averaged across subject and stimulus presentation method. The high and low luminance levels are represented by the filled and unfilled symbols, respectively. The letters A through E represent the stimulus separation distances. Their values are, respectively, 1.0, 2.5, 5.0, 7.5 and 10.0 deg of visual angle. Lines of best fit were fit to the data by eye.

All of the functions were linear and nearly all of the functions had slopes around 1.0. Only the 10 deg stimulus separation distance produced functions with slopes significantly different from 1.0. The slopes of these functions are presented in Table 7.

It appears that the brightness matching technique and the magnitude estimation task have about the same precision for



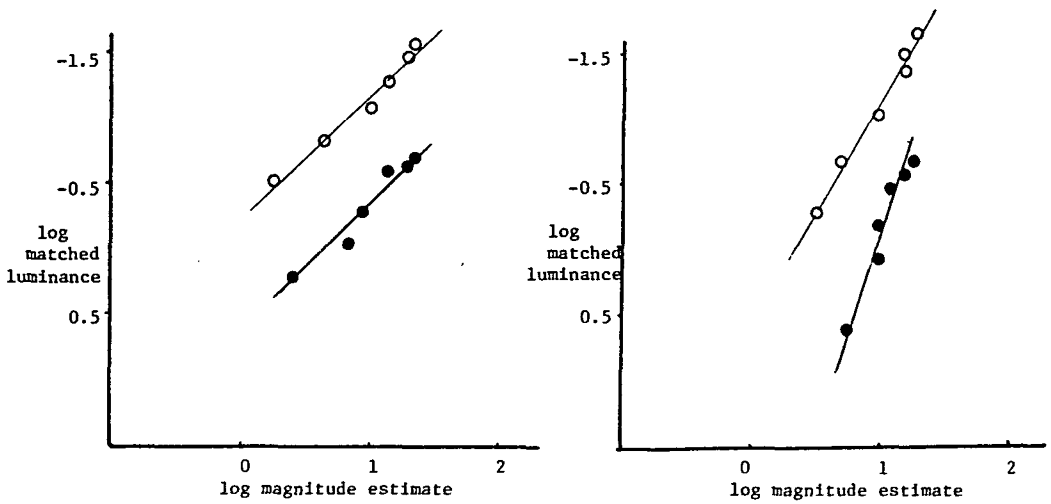


Fig 12. Log matched luminance as a function of log magnitude estimate. Filled symbols represent the high luminance level and unfilled symbols represent the low luminance level. The letters A through E represent the stimulus separation distances. Their respective values are 1.0, 2.5, 5.0, 7.5 and 10.0 deg of visual angle.

Table 7

Slope values for log matched luminance as a function of log magnitude estimate

Separation	Luminance	Slope
1.0	high	1.33
1.0	low	0.72
2.5	high	1.20
2.5	low	0.80
5.0	high	1.40
5.0	low	0.89
7.5	high	1.00
7.5	low	1.03
10.0	high	3.00
10.0	low	2.00

assessing spatial summation effects. That is, the scaling functions and brightness matching functions are equivalent under conditions of size-induced brightness. Similar findings have been reported previously in the literature.

Cavonius and Hilz (1973) compared the two methods for determining spectral sensitivity. In this study, achromatic lights were matched for brightness to monochromatic lights and monochromatic lights were scaled for brightness. The authors found virtually no difference between the spectral sensitivity curve determined by scaling and the curve determined by brightness matching.

Fuld and O'Donnell (in press) used both brightness matching and magnitude estimation methods to measure contrast-induced brightness in the Ehrenstein illusion. In this study, a spot of light, invariant in size, was matched for brightness to Ehrenstein patterns that varied in the size of their central gap area. In addition, the aforementioned Ehrenstein patterns were scaled for brightness. When log estimated brightness was plotted as a function of log matched luminance for these data, a linear function with a slope of 1.1 was produced. Thus, no difference between the brightness assessment methods was obtained.

The same authors presented to their subjects Ehrenstein patterns that varied in number of lines used to create the pattern as well. Again, a spot of light that remained constant in size was matched in brightness to each pattern, and the patterns were scaled for brightness. No difference was found between the magnitude estimation curve and the brightness matching curve derived from these stimulus patterns.

It appears that brightness matching and magnitude estimation are equally sensitive measures of brightness. This has been reported for the brightness of monochromatic lights and contrast-induced brightness. The present research suggests that it is also true for size-induced brightness or spatial summation.

There is no clear explanation for the large slope values found at the 10 deg stimulus separation distance. It offers an interesting possibility that the two brightness assessment methods become less similar when they are used with stimuli presented at 5 deg retinal eccentricity or greater. A comparison of the brightness matching and magnitude estimation techniques at various retinal location greater than 5 deg is suggested.

Conclusion

The present research effort both corroborated and expanded existing knowledge on suprathreshold spatial summation effects. As reported in the literature, brightness was found to increase as stimulus area increased. These effects were found to be greater when luminance level was low than when luminance level was high. This finding also supported findings reported in the literature.

There were also a number of unique contributions from the present research. The effect of stimulus presentation method on spatial summation is one novel contribution. A surprising result of the present study was that method of stimulus presentation had no effect on spatial summation and apparent brightness. Both binocular and haploscopic stimulus presentation conditions yielded similar results. This suggests that control for glare between fields is unnecessary at the luminance levels used in the present study. Information of this sort will be useful to researchers that design future suprathreshold spatial summation experiments.

Another unique contribution of the present research is the comparison bétween the brightness matching technique and the magnitude estimation technique for measuring suprathrehsold spatial summation effects. It was found that the two brightness assessment techniques yielded similar results. Spatial summation effects were discovered using the brightness matching technique and the magnitude estimation technique. In addition, results from both techniques showed a difference in the amount of spatial summation produced at the various luminance levels. Log matched luminance was plotted as a function of log magnitude estimate for both luminances and all stimulus separation distances. All the functions were linear and nearly all the functions had a slope of 1.0. This suggests that the two psychophysical procedures are equivalent tools for assessing suprathreshold spatial summation effects, when the stimuli are presented at retinal eccentricities of less than 5 deg. Further research is needed to clarify what effect retinal eccentricities greater than 5 deg have on the similarity of the two brightness assessment methods.

A third unique contribution was the effect of retinal eccentricity on spatial summation that was suggested in the present research effort. A minimum amount of spatial summation was found to occur around 2.5 deg retinal eccentricity in the present study.

If retinal location proves to influence the production of spatial summation effects, this will be an important factor to consider in the design of future suprathreshold spatial summation experiments. Further clarification is needed, however, on the validity of this effect.

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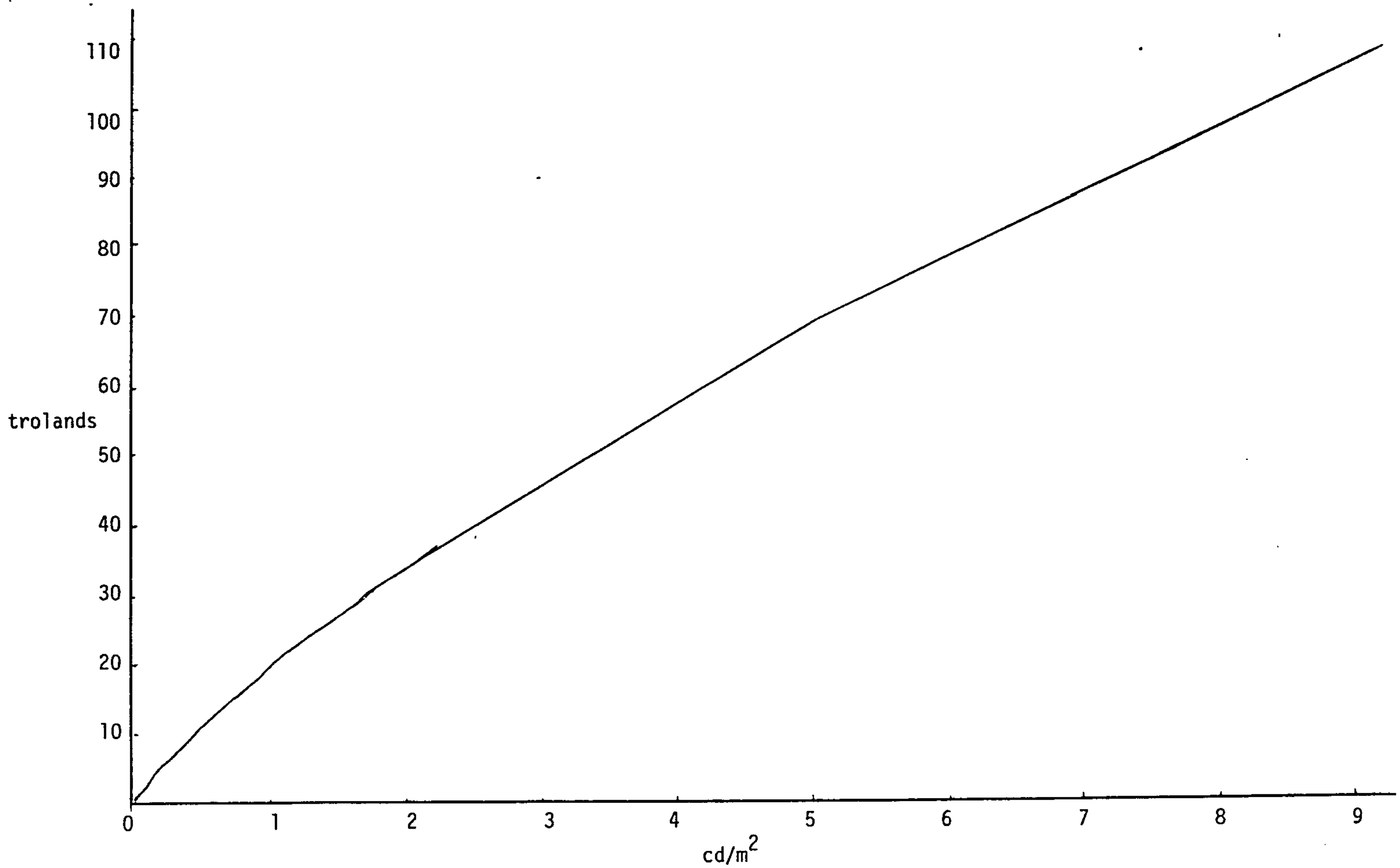
APPENDIX



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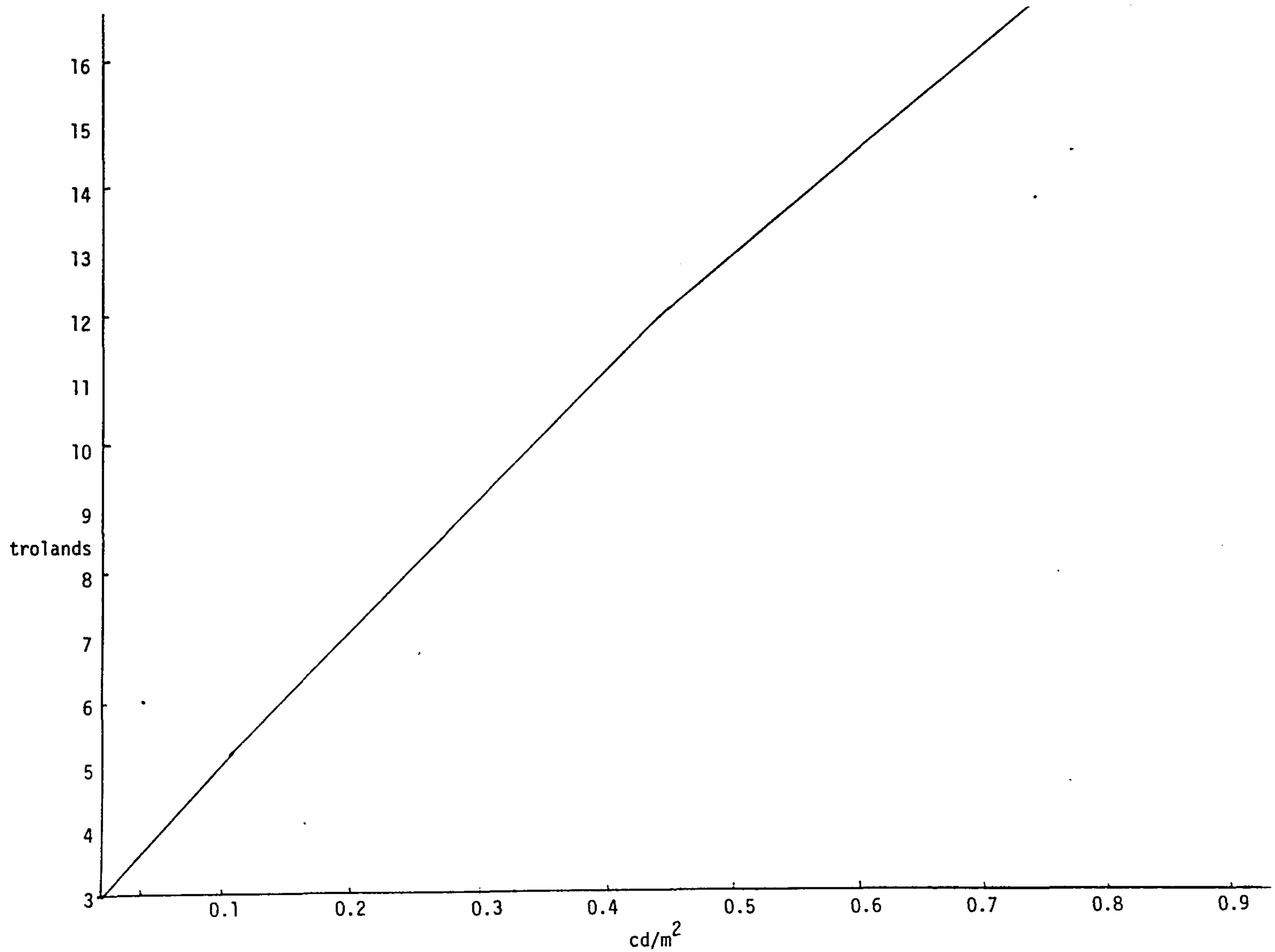

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